The use of multispectral remote sensing in the management of the North York moors

Weaver, Ruth E.

The Use of Multispectral Remote Sensing in the Management of the North York Moors

Ruth E. Weaver B. A. (Hons.) Reading

Thesis presented for the degree of Ph. D at the University of Durham.

The Use of Multi-spectral Remote Sensing in the Management of the North York Moors

Ruth. E. Weaver

ABSTRACT

This thesis examines the use of multi-spectral remotely sensed data in the management of the North York Moors, an upland area of heather moorland in northern England. A series of ground radiometer surveys and airborne simulations are analysed to determine the relative importance of spatial, spectral and temporal resolution as characteristics of earth resources satellites in this environment. Particular reference is made to the potential for selecting and combining data from the Landsat MSS, TM and the SPOT HRV sensors.

The results show that spectral resolution can be critical in isolating and recognising elements of the moorland community by their spectral response, especially at the most detailed levels of vegetational description. Temporal resolution has little effect on the discrimination of targets within the heather dominated areas but affects the separability of the major communities of heather, bracken and sedges. Change in spatial resolution has no clear effect on the spectral uniformity and spectral separation of the elements of the heather dominated areas. The interaction between spectral and spatial resolution is more important in isolating the major communities, where the requirement for spatial precision is balanced against the need to suppress spectral variation within the moorland.

The hypothesis that multi-spectral remotely sensed data can provide critical information on the distribution and status of moorland vegetation is not refuted in this thesis. Remotely sensed data would make the greatest contribution to management if linked to other spatial data as part of a Geographical Information System. In the absence of such a formal structure satellite imagery can still provide a regular and unique inventory of the moorland habitat which will increase the efficiency of management.

This thesis and the research reported in it have been undertaken solely by myself. No part of it has been submitted for a degree in this or any other University

Acknowledgements

The research reported in this thesis was undertaken in the Department of Geography, University of Durham under the supervision of Dr. Ray Harris, with additional support from Prof. Ian Simmons. I am grateful for their practical advice and constructive criticism throughout the research period and especially in the writing up stages. The work was financed by a post-graduate studentship from the Natural Environment Research Council (NERC). The NERC also purchased the ground radiometer, provided data under the airborne simulation campaigns of 1983 and 1984 and made possible a visit to American research institutes in the summer of 1983. Further data were provided by the National Remote Sensing Centre as part of the 1984 SPOT simulation campaign.

A number of people provided facilities and advice which reduced practical problems to manageable proportions. In particular, the advisors and operators of the Computing Centre at Durham met my demands for access to tapes and disk space with great good humour and efficiency. The photographic and cartographic sections of the Geography department were adept at turning negatives and sketches into professional displays at the eleventh hour. Jonathan Oldham helped to collect ground radiometer data in August 1983 and Jacky Webb at the University of Southampton gave instruction in calibrating the instrument.

The owners of the Wykeham Estate on the North Yorks Moors kindly let me trample their heather in the pursuit of knowledge. Dr. Roy Brown of the North York Moors National Park proved an invaluable source of information and enthusiasm and I am deeply grateful for his constant support and encouragement.

I have benefited greatly from the academic interest, companionship and general shining example of the postgraduates at Durham and latterly at Aberdeen. David, Gill, Sinclair and Charlie in particular made Durham a better place. Finally, this work would not have been started or completed without the steadfast support of my parents over the last twenty-seven years, for which I am profoundly grateful.

CONTENTS

List of Tables page

List of Figures page

Chapter One: Aims, background and structure

1.1 Introduction

This thesis examines the feasibility of using remote sensing in the management of a specific semi-natural environment, heather moorland in upland Britain. The work concentrates on the importance of spatial, spectral and temporal resolution as characteristics of airborne multispectral scanner data and considers the implications of these results for the use of data from the Landsat Multi-Spectral Scanner (MSS), Thematic Mapper (TM) and the SPOT Haute Resolution Visible (HRV) sensors.

Remote sensing is the set of techniques used to obtain information about the earth's surface and atmosphere at some distance from them, usually by means of radiation from the electro-magnetic spectrum (Townshend, 1981a). The term remote sensing was coined by the Geographical Office of Naval Research (USA) during tests on lunar analogue surfaces as part of the Apollo space programme (Lintz and Simonett, 1976).

Satellite remote sensing data are used routinely in meteorological monitoring, crop yield forecasting and exploration geology, where there is a clear and direct return on investment by government or commercial interests. As concern increases over the depletion of natural resources and the conservation or protection of the environment, there is a growing need for regular, comprehensive and accurate information on the quantity and condition of world resources. In the past decade, this need has started to be met by an increase in the experimental use of satellite remote sensing. At a global scale, NASA's Global Habitability programme (NASA, 1984a) aims to understand and predict the long-term effects of fluctuation in the biogeophysical and biogeochemical cycles which exchange water, light and essential elements between the oceans, the atmosphere and the land. At a more practical level, remote sensing has been shown to be useful for rangeland monitoring (Griffiths and Collins, 1983; Justice and Hiernaux, 1986), water prospecting (Salman, 1983), location of fuelwood

(Nichol, 1983) and detailed agricultural inventory (Thiruvengadachari, 1983; Roy et al., 1985) in developing countries.

Projects throughout the world report on the use of remote sensing for the description and monitoring of ecosytems such as salt marshes and wetlands, heathland, grassland, lakeshores and ice-caps (Baker, 1981; Jensen et. al., 1986; Milton et al., 1986; Rose and Rosendahl, 1979; Schneider et al., 1985; Birnie and Williams, 1985). Remote sensing techniques are now gaining acceptance for the collection and analysis of data on wildlife habitats or direct wildlife inventory (Carneggie et al., 1983; Schwaller et al., 1984; Hielkema et al., 1986; Anderson et al., 1980). Such experimental work has demonstrated that remote sensing data have an application in a wide range of management problems in the natural and semi-natural environment.

Since the launch of Landsat 1 in 1972, there has been a proliferation of satellite systems and sensors which cover the electro-magnetic spectrum from visible to microwave wavelengths at varying spatial, spectral and radiometric resolutions. Only a small part of this wealth of data will be relevant to one management problem. If remote sensing is to be a practical tool in resource management the most appropriate data must be identified and acquired. Because of the great diversity of information that is pertinent to natural resource management, this problem of data selection will recur and will increase in importance with the diversity of sensor systems in orbit by the 1990s.

This thesis examines the possibilities of using remote sensing data in the management of moorland in upland Britain. The North York Moors in northern England are used as a type example throughout. The open heather moors are a delicately balanced ecosystem, under considerable and continuing pressure from changes in the intensity of agriculture and informal recreation. The work has been developed in close collaboration with officers of the North York Moors National Park to ensure that the research deals with the immediate practicalities of moorland management.

This chapter deals with the rationale for the thesis. The concepts of spectral, spatial, radiometric and temporal resolution are defined and outlined briefly in section 1.2. In section 1.3 the specific hypotheses to be tested are stated and discussed in relation to these concepts and the practical objectives of the thesis. This section also contains an outline of the relationship between data from the airborne scanner and data from the satellite sensors. This is followed in section 1.4 by short descriptions of the development of remote sensing, current trends in system design and their implication for the user. The importance of the gaps that exist between the system designers, the research scientists and the reality of a commercial user market are discussed in relation to this work in section 1.5.

1.2 System Parameters

Remote sensing instruments measure the amount of radiation reflected by or emitted from an object in selected parts of the electro-magnetic spectrum. The terminology used to describe the interaction of electro-magnetic energy with ground targets is given in table 1.1. The interpretation of remote sensing data centres on the detection and identification of ground features by differences in their spectral response. The amount of reflectance or emittance from a vegetated target is controlled by one or more physiological or structural features of the plant and the plant canopy. The discriminating information in remote sensing data therefore depends on whether the principle sources of differentiation between the targets are recorded by their response in the wavebands measured.

The information in an image is not however a simple function of the spectral parameters of the system. The efficacy of the system's spectral resolution is affected by the spatial, temporal and radiometric characteristics of the system and the spectral, spatial and temporal characteristics of the target.

The spectral resolution of a system is defined by the number, positioning

Radiant energy	Total energy radiated by a surface in all directions
Radiant flux	Radiant energy per unit time
Radiant exitance	Radiant energy per unit time per unit area
Irradiance	Total energy radiated onto unit area in unit time
Radiance	Total energy radiated by a unit area per solid angle of measurement in unit time
Spectral radiance	Radiance in specified wavelengths
Reflectance	Ratio of radiance to irradiance

Table 1.1 Remote sensing terminology

The definitions above are taken from Curran (1985). In the reflective wavelengths radiance approximates the amount of energy which is reflected and there is clearly some confusion in the literature over the use of the terms radiance and reflectance. A remote sensing system measures spectral radiance. Reflectance is strictly a unitless ratio measure.

and width of the wavebands it carries. The experimental Airborne Imaging Spectrometer (AIS) of NASA (NASA, 1984b) has a number of narrow bandpasses at specific points of the spectrum. Targets, especially minerals, which have diagnostic reflectance characteristics in these bands can be identified in AIS data. In comparison the Landsat TM and MSS and the SPOT HRV systems have broad wavebands and undersample the spectrum. However the spectral resolution of the TM is an improvement over that of the MSS. The TM extends the wavelengths sensed into the mid- and thermal infrared (IR) and reduces the bandwidths of the visible and near-IR wavebands. The relationships between vegetation and radiance and the precise positioning of wavebands are discussed in chapter 2.

Spatial resolution is the distance by which two objects must be separated on the ground before they can be separated with confidence in an image (Townshend, 1981b). The spatial resolution of a sensor is defined as a physical distance by the ground projection of a detector element when at orbital height, but the spectral characteristics of the target are an important determinant of the effective spatial resolution in an image. Targets under the nominal resolution may be visible if they are of high contrast with their surroundings. Conversely, targets of low contrast may not be detected even if they exceed the nominal spatial resolution. The factors which determine the effective spatial resolution of an image are discussed in chapter 2.

The radiometric resolution of a system is the number of voltage steps into which the analogue output of the sensor is digitised. Given sufficient image processing power, when the data are displayed in image form this controls the number of discrete grey tones in the image. Radiometric resolution therefore determines the subtlety with which targets can be discriminated in a given waveband. Radiometric resolution is controlled by the noise level of the detector and the absolute amount of energy that reaches the detector. It is therefore linked to spectral and spatial resolution as narrow bandwidths and a small instantaneous field of view allows only a small radiant flux at the sensor.

Temporal resolution refers to the time at which data are acquired relative to any temporal periodicity in the radiance of the target. It is particularly relevant to targets containing vegetation canopies, where specific communities may be identified only at certain times in the growth cycle. The use of data collected at different points in the growing season can therefore effectively increase the spectral dimensions of the data set.

The relative importance of spectral, radiometric, spatial and temporal resolution depends on the complexity of the scene and the information that is required. Trade-offs are made between the resolution parameters in the design of the sensor system and in the choice and interpretation of the data. These are discussed in greater detail in chapter 2. The resolution characteristics of a system or an image are likely to be sub-optimal for at least some of the targets of interest and this is exacerbated by the common need to monitor communities at more than one scale. The logical solution is to overlay a number of data sets as different levels in a spatially referenced databank or Geographic Information System (GIS) and, for each task, extract information from the most appropriate combination of layers. This thesis lays the foundation for a GIS approach to the use of remotely sensed data for monitoring moorland vegetation. The spectral and spatial discrimination of a number of common moorland communities is examined in a series of airborne and one satellite sensor data sets which have different spectral, spatial and temporal characteristics. The results define the importance of spectral, spatial and temporal resolution for a number of management problems and suggest the way in which data from satellite sensors such as the Landsat MSS, TM and the SPOT HRV might best be combined to give the maximum useful information about the moorland community.

1.3 Thesis structure

The programme of research is ordered around a series of hypotheses, set out in Figure 1.1. This approach has forced a clear structuring of the research and the thesis and follows Popper's arguments on the nature of scientific research (Popper, 1974). Popper contends that there is little value in the inductive processes of observation and description, and that the best science results when bold hypotheses are exposed to critical refutation. Science then advances by the survival of hypotheses which resist refutation (Sugden and Birnie, 1983).

The working hypothesis is that remote sensing data can provide sufficient critical information on the distribution and status of moorland vegetation to make their use an important element of management. Subsequent more rigorous hypotheses examine the importance of individual resolution parameters. Individual chapters of the thesis also deal with the technical details of the data used and the problems of moorland management.

Chapter 2 is a technical description of the Daedalus airborne scanner and the Landsat MSS, Landsat TM and SPOT HRV satellite systems. With the exception of the Landsat MSS data discussed in chapter 7, all the digital multispectral scanner data used in this thesis were acquired by the Daedalus scanner mounted in a light aircraft. These data are not a direct simulation of those available from the satellite sensors for reasons discussed in chapter 2 and the results are interpreted accordingly. Chapter 2 also examines the effect of the spectral parameters of each satellite sensor system on the information available from its data for vegetated targets. Sources of error introduced by the sensor and the sensing process are discussed and their effect on the accuracy and reliability of the data is assessed.

The justification for concentrating on the moorland ecosystem is given in Chapter 3. It is followed by a brief introduction to the ecology and management of moorland areas, and a description of the specific management problems of the North York Moors. It is shown that conventional vegetation analysis and the techniques used in interpreting remote sensing data describe the distribution of a vegetation community in the same way. Both

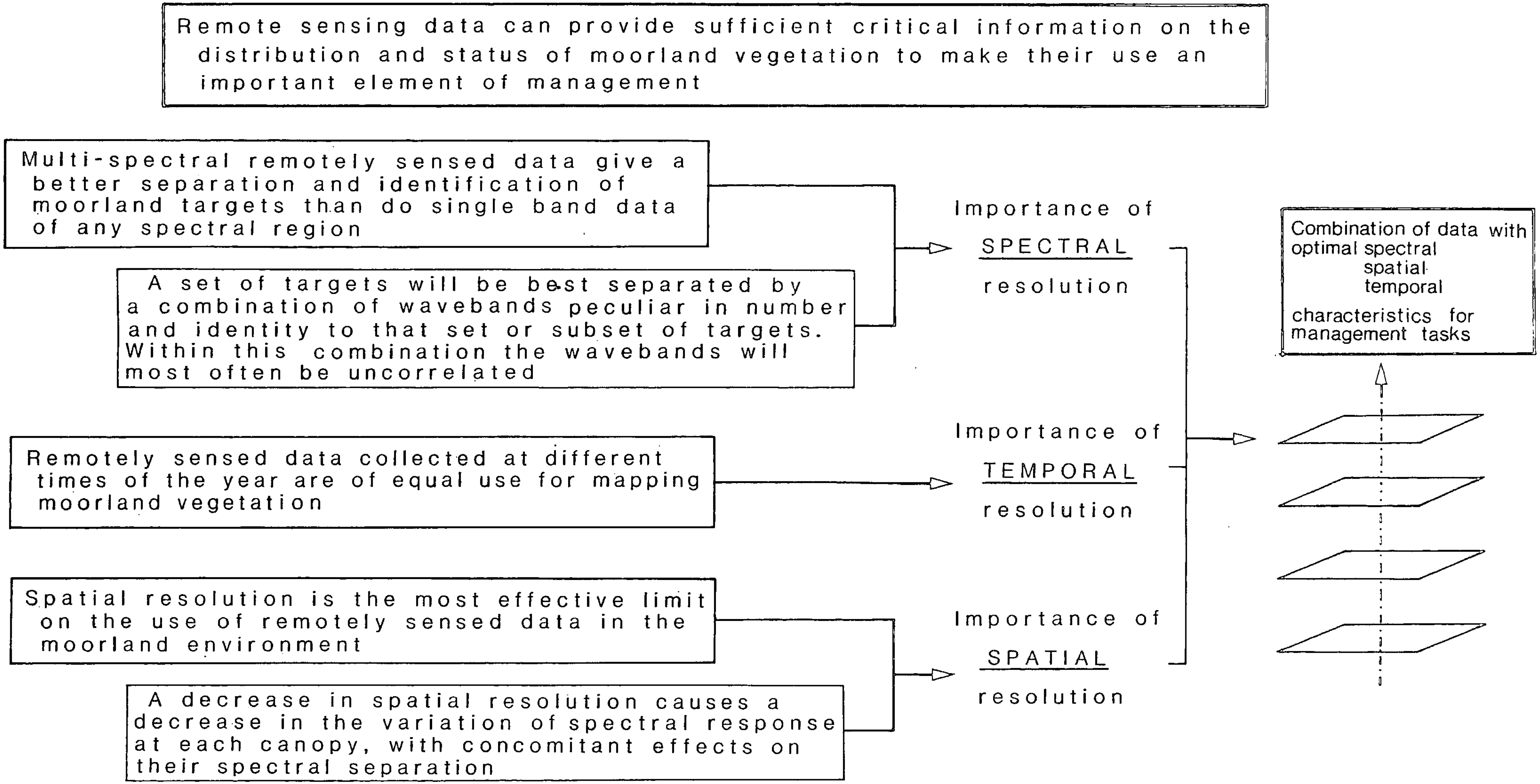


Figure 1.1 Structure of research

seek to discriminate between groups of elements which have similar attributes. Because the wavebands of earth resources sensors are sensitive to important characteristics of vegetated canopies, groups isolated by one method should also be isolated by the other.

The collection and analysis of ground radiometer data for common moorland canopies is reported in chapter 4. This is accompanied by a detailed description of the vegetation present in the study area. A comparison of the information in the two data sets shows that similar groupings can be found in both, which confirms the proposals of chapter 3. The agreement is sufficient to warrant a fuller investigation of the aircraft and satellite data.

Chapters 5, 6 and 7 report on the analysis of the multispectral scanner data. As far as possible spectral, temporal and spatial resolution are considered separately. It was not possible to emulate recent work (Anuta, 1984; Williams et al., 1984; Acevedo et al., 1984) which systematically degrade a basic high resolution data set in order to mimic the parameters of each system in the study. This methodology is desirable in that it allows particular parameters to be varied whilst all others are held constant, but has the drawback for this work that the emphasis of the research becomes the data per se rather than their application.

The spectral information in the airborne scanner (Airborne Thematic Mapper or ATM) data is analysed in chapter 5. The working hypothesis is that, when available, a multispectral data set invariably holds more information than a single band set of any spectral region. This premise is introduced and justified in chapter 2. In chapter 5 it is refined after discussion to a more relevant and testable suggestion, namely that the number and identity of wavebands in the data set is critical, and that there will be one subset of wavebands which discriminates a given pair or group of vegetation types better than any other set. The number and identity of the elements in this set will be specific to the vegetation types to be discriminated. When tested by an analysis of the statistical separability of test classes this modified hypothesis was refuted in only a few cases. Each of the 7 ATM bands used was found to be important for the discrimination of one or more sub-groups of vegetation, although some combinations of bands returned a consistently good performance. The practical implication is that the number of wavebands used can be reduced, thus saving time and money at the interpretation stage, but a slightly different combination of bands is needed for each element of the management problem. Chapter 5 also includes a brief assessment of the value of measures of statistical separability as subsitutes for image-based classification in this environment.

Chapter 6 examines the importance of temporal resolution, using ATM data collected under the MSS 83 and MSS 84 campaigns organised by the Natural Environment Research Council (Williams, 1984). The hypothesis (fig. 1.1) is that remote sensing data acquired at different times of the year are of equal use for the mapping of moorland vegetation. This hypothesis is based on the fact that there is little marked seasonality within the moorland community. The acquisition date may however be important in identifying communities such as sedges and bracken which have distinctive annual growth cycles. The analysis in this chapter follows the pattern of chapter 5 and examines the discriminatory information in single wavebands, the full feature space and selected subsets of wavebands for data acquired in May and August. Despite some technical problems with the data the results were sufficient to refute the hypothesis and show that the date of acquisition can be important in discriminating between some elements of the moorland community.

Chapter 7 examines the importance of spatial resolution. The general hypothesis (fig 1.1) is that spatial resolution is the most effective limit on the utility of remote sensing data. The spatial resolution of a sensor affects data quality in two ways, by setting an approximate lower limit on the size of targets that can be identified, and by affecting the variability of spectral response within a target. Objects cannot be isolated by their spectral response if they are too small to be detected in the imagery. Conversely, the spectral detail in data with a fine spatial resolution can obscure significant divisions in land cover which occur at a broader scale. Therefore an optimum spatial resolution will exist for each target at which it is clearly defined in the imagery, with a minimum proportion of boundary pixels and a maximum spectral homogeneity. In the moorland community the optimal spatial resolution will be different for different management tasks as the level of detail needed in the description of the vegetation is also a spatial division. Chapter 7 examines the effect that decreasing spatial resolution has on the spectral separation of the targets identified in chapters 5 and 6.

Chapter 8 brings together the results of the thesis and assesses the importance of spectral, spatial and temporal resolution in identifying elements of the moorland community in ATM data. The discussion examines the implications of these results for the use of satellite sensor data in moorland management and the validity of the basic hypothesis (fig 1.1). The results show that there are real possibilities for the incorporation of multispectral remote sensing into the day to day management of moorland areas and chapter 8 describes how this might best be done.

1.4 Development of remote sensing

The following three sections outline the development of remote sensing to date, the range of satellite systems that will be available by the 1990s and the problems of communication which exist between system designers, research scientists and the commercial user community. The first two are an important background to this thesis. They describe the rapidity with which the technical capabilities of satellite remote sensing have developed and the choice of systems and data which will face the user in the next decade. The third section examines the current mismatch of interests between system hardware designers, academic users of remote sensing data and the end users who operate in a commercial environment. The capabilities to design and build a sensor currently outstrip the ability of the user community to use its data. Clearly, as satellite systems such as SPOT and Landsat are now run on a commercial basis it is important that the current and potential user community is widened and that dialogue between all groups is increased.

1.4.1 Past growth of remote sensing

Until the 1960s, aerial photography was the principle method of operational remote sensing. Its development was accelerated by reconnaissance needs in both World Wars. Following its use in World War I air photography became a routine tool in the civilian fields of geology, land use survey and cartography (Simonett, 1983). This led to great improvements in the design of cameras and film and in equipment and techniques for photointerpretation. Air photo reconnaissance was used extensively during World War II, which also saw the beginnings of airborne thermal IR and radar systems.

After World War II civilian remote sensing continued to build on the military experience, expanding from panchromatic to multiband systems. In particular, interest centred on use of the short wavelength IR region, which was known by the end of World War II to contain information on vegetation condition. Krinov's work (Krinov, 1947) on multispectral reflectance had already received some attention and Colwell's experiments (Colwell, 1956) document the early civilian use of colour IR film to detect vegetation stress and disease.

The need for repetitive monitoring of crop and forest areas had been recognised in the USA by the late 1950s. Multiband camera systems were developed which allowed images to be recorded simultaneously through several different filters (Simonett, 1983). However, interpretation of these data was largely by eye, slow and prone to discrepancies between operators. In 1960, the US Department of Agriculture recommended that a committee be set up to study the potential of aerial surveys in the provision of "timely and accurate" information on crop and forest diseases. The committee noted that there was a clear need for a highly automated approach to this data gathering (MacDonald, 1984).

By the early 1960s, the committee was focussing on preliminary research in progress on the use of an airborne multispectral scanner. The instrument was developed at the University of Michigan for a military contract. The combined use of rapid-acting, sensitive detectors, optical viewing elements and detector preamplifiers had made possible the development of an airborne imaging spectrophotometer operating at ultraviolet, visible and infrared wavelengths. In 1964 the existing military classification regulations were revised to allow access to the data acquired by the Michigan scanner (MacDonald, 1984). The Michigan instrument formed the basis for modern optical-mechanical scanners and precipitated the development of agricultural remote sensing. The scanner data have three major advantages over photographic systems:

i. The data are acquired, stored and manipulated in digital form. They are therefore amenable to computer assisted quantitative analysis, which introduces an objective, repeatable approach to data analysis.

ii. The uncertainties introduced by photographic emulsions and processing are avoided, and radiometric and geometric corrections are simplified.

iii. Scanners are able to collect data at wavelengths up to 14 µm, as opposed to an upper limit of 0.9 µm for photographic systems.

Overall, the introduction of digital, multispectral scanners initiated a greater flexibility in acquiring, comparing and integrating large spectral data sets, with results reproducible by other researchers. This established the trend in remote sensing towards computer assisted analysis of multispectral data.

The introduction of spacecraft as remote sensing platforms came in the late 1950s and was initiated by NASA, in conjunction with researchers in geology and agriculture. The first space photographs for geological research were taken from the Gemini-Titan mission in 1965, although earlier snapshots were available from the Explorer 6 mission in 1959 and from a camera on the unmanned Mercury-Atlas mission of 1960 (Simonett, 1983). Subsequent Gemini-Titan missions acquired photography of ocean glitter and terrain features on a standing request basis (Simonett, 1983). Many of these images have been published by NASA (NASA 1967a, 1967b, in Simonett, 1983). These data provided the basis for a set of preferred parameters for remote sensing drawn up by the United States Geological Survey. These in turn formed the basis for the Survey's Earth Resources Observation Satellite (EROS) programme, and the geological input to the Earth Resources Technology Satellite (ERTS) -1, later Landsat-1.

Interest in remote sensing of the earth was given a further impetus in the run up to the Apollo lunar missions. Remote sensors were to be placed in orbit around the moon to test the suitability of the lunar surface to receive a landing craft. These were tested as airborne, preflight models over lunar analogue surfaces on the earth. It was soon apparent that the instruments had considerable general utility and the programme was expanded to include geological, oceanographic and agricultural targets (Lintz and Simonett, 1976).

Steady progress had been made in experiments with the Michigan scanner through to 1967. On the basis of this work, a consortium of research groups, involved in remote sensing of agricultural targets, recommended specific experiments from space, and gave specifications for an ERTS-1 sensor to NASA in 1968. The first multispectral space experiment was carried out from Apollo 9, where astronauts used 70mm cameras to take simultaneous photographs at green, red and near infrared wavelengths.

The ERTS programme was finally approved at the federal level in January 1969 (MacDonald, 1984). In the original plan, a single sensor, the Return Beam Vidicon (RBV) camera, was suggested by a NASA study group as the appropriate instrument for the first system. This followed the framing nature of the previous space experiments. The USGS proposals agreed with this, and suggested a three camera system, with red and near-IR wavebands. The final NASA RBV system had green, red and near-IR bands. The US Department of Agriculture required greater spectral information, and pressed for a second sensor along the lines of the Michigan scanner. This was included as the Multispectral Scanner system (MSS), although it was a relatively crude instrument compared to the airborne system (Freden and Gordon, 1983; MacDonald, 1984).

This two instrument configuration was flown on the first three Landsat platforms, with minor modifications to the RBV, and the inclusion of an experimental thermal IR band on the MSS of Landsat 3. The RBV has been replaced by the Thematic Mapper on Landsat 4 and Landsat 5. The Landsat MSS data are now widely established for use in earth resources monitoring.

Although Landsat was the first satellite dedicated to earth observation, meteorological systems had been in operational use from the 1960s. These have been steadily upgraded and improved to the current TIROS-N series. NASA has also launched a sequence of experimental satellites, the details of which are given in Table 1.2. They include Skylab (the first American space station), the Heat Capacity Mapping Mission (HCMM) which examined the use of thermal inertia as a method of mapping soil moisture, and Seasat, which carried a suite of radar sensors to monitor sea state. The data from the Seasat altimeter are of such high accuracy that they and the instrument are now under security classification (Henderson,1984).

The launch of the first Space Shuttle in 1981 marked a new direction in remote sensing. Experimental sensors can be flown on short missions. The sensor can be returned, modified and reflown without a dedicated platform for each stage. This philosophy has been taken up by Europe in the development of the reusable EURECA satellite (Pardoe, 1985).

The current impetus of research in Europe and the USA is in the collaborative development of a manned space station, to be operative in the 1990s, with a life expectancy of 30 years. The European contribution to the Space Station is being developed under the Columbus Programme and within this the UK is responsible for the design and construction of one or more multi-sensor polar orbiting platforms (Hardy et al., 1987).

1.4.2 Systems under design and development.

Tables 1.2 to 1.5 list a number of past, present and future satellite and airborne remote sensing systems. The contents are drawn largely from Slater (1985). The acronyms used in the discussion below are given in full in the tables.

Earth resources satellites to date are characterised by relatively low spatial, spectral and radiometric resolution (table 1.2). The Landsat MSS represents the middle ground, with four wavebands, three of 100nm width, and one of 300nm, a spatial resolution of approximately 79m, and 6 bit quantization. Sensors such as the AVHRR and the CZCS which have more wavebands or higher quantization have a lower spatial resolution.

In contrast, the S-192, MOMS, and NASA's Ocean Colour Experiment (see Slater, 1985) sensors have high spatial and spectral resolution. All have been flown as experiments on recent Shuttle missions.

The most recent sensors designed for regular use are the Landsat Thematic Mapper and the French SPOT HRV systems. The TM extends the spectral range of the MSS, and has higher spatial and spectral resolution. These improvements are the result of advances in the engineering aspects of system design, and an increased understanding of the relationships between vegetation and spectral response. The TM is described as the first of a second generation of earth resources satellites (USGS, 1982), which will have high spectral and spatial resolution, the details of which are to be decided by consultation with the user community.

In the past, the configuration of airborne systems (Table 1.3) has been an accurate indicator of the parameters of later satellite systems. The Bendix M2S and the Daedalus AADS series continue the experiments started with the Michigan scanner and collect data in narrow spectral bands in a similar way to the orbiting TM sensor. Experiments with the airborne

System details as available - scanner name and acronym - country of origin - purpose; platform	Scanner details as available - mechanical/linear array - wavebands; spatial resolution
AVHRR: Advanced Very High Resolution Radiometer. USA meteorology; TIROS-N	mechanical scanner 1100m x 1100m 1 visible (vis) 1 near-IR (n-IR) 1 mid-IR (m-IR) 2 thermal IR (t-IR)
Bhaskara-2 India earth resources	TV camera 1000m x 1000m 1 vis 1 n-IR
CZCS: Coastal Zone Colour Scanner USA ocean monitoring; Nimbus	mechanical scanner 800m x 800m 6 visible 3 n-IR
FILE: Feature Identification and Location experiment USA Shuttle	CCD area array camera 1000m 1 vis x 750m 1 n-IR
HRV: Haute Resolution Visible France/Belgium/Sweden earth resources; SPOT	CCD 1 broad band panchromatic 10m x 10m and 2 vis 20m x 20m 1 n-IR
HCMR: Heat Capacity Mapping Radiometer USA Soil moisture mapping; HCMM	mechanical scanner 1 visible 500m x 500m 1 t-IR 600m x 600m
MSS: Multi-spectral Scanner USA earth resources; Landsat 1-5	mechanical scanner 2 vis 79m x 56m 2 n-IR
RBV: Return Beam Vidicon camera USA (U.S. Geol Survey) earth resources; Landsat 1-3	camera 30m x 30m 2 vis 1 n-IR
TM: Thematic Mapper USA earth resources; Landsat 4-5	mechanical scanner 3 vis 30m x 30m 1 n-IR, 2 m-IR 1 t-IR 120m x 120m
MOMS: Modular Opto-electronic Multi-spectral Scanner earth resources; Shuttle	CCD array 1 vis 1 n-IR
S-192: part of Earth Resources Experiment Package on Skylab	conical scanner 87m x 87m 5 vis 4 n-IR 3 m-IR, 1 t-IR

Table 1.2 Current and past satellite systems

System details as available - scanner name and acronym - country of origin - purpose	Scanner details as available - mechanical/pushbroom scanner - wavebands
Daedalus AADS 1260 AADS 1268 USA (commercial)	mechanical scanner 1260: 7 vis, 3 near-IR, 1 thermal-IR 1268: 5 vis, 3 n-IR, 2 m-IR, 1 t-IR
Airborne Imaging Spectrometer (AIS) USA, Jet Propulsion Lab.	128 wavebands, each of 10nm width in area 1.2 - 2.4um
Fraunhofer Line Discriminator USA To detect solar stimulated luminesecence. See Slater (1980)	Fraunhofer absorption lines 656.3nm 589.0nm 518.4nm 486.1nm 422.7nm filter has half-power width of 0.1nm
M2S Modular Multiband Scanner USA (commercial)	8 vis 3 n-IR
MI7: derived from Michigan scanner used in Cornblight watch experiment. USA	8 vis 1 n-IR 3 m-IR 1 t-IR
Multispectral Electroptical Imaging Spectrometer Canada	5 vis 3 n-IR CCD system developed for Canada Centre for Remote Sensing
NS - 001 Johnson Space Centre Landsat MSS/TM simulator	3 vis 2 n-IR 2 m-IR, 1 t-IR
CNES pusbroom scanner	4 bands from range 0.4-1.1 (and m-IR planned), to simulate SPOT HRV sensor.
SWIR-LAPR Short-wave IR Line Array Pushbroom Radiometer NASA Goddard- geological work	single band from 1.0 - 1.5 µm 1.61 - 1.69 µm 2.14 - 2.30 µm 3 systems in use
TIMS Thermal IR Multispectral Scanner. Made by Daedalus, used by NASA/NSTL Earth Resources Lab.	6 t-IR
U-2 TMS TM simulator flown at 20km altitude for NASA Ames	11 band total, 7 as TM
Supercyclope - Societe Anonyme de Telecommunication.	2 m-IR 2 t-IR

Table 1.3 Current and past airborne systems.

System details as available - Scanner name and acronym - country of origin - purpose	Scanner details as available - mechanical/CCD array - wavebands; spatial resolution
AEROS-A: Advanced Earth Resources Oservation Satellite USA earth resources	Two linear arrays, each with 2 visible (vis) 80m x 80m 2 near-IR (n-IR) one at 45m x 45m one at 80m x 80m
ERS-1: Earth Resources Satellite Japan earth resources	linear array 4 bands 0.5 - 1.1 um 80m x 80m
IRS: India Resource Satellite India earth resources	sensor 1A: 3 linear imaging sensors each with 4 bands in vis and near-IR sensor 1B: planned resolution of 15-20m IRS-2 to include mid- and thermal IR
Mapsat USA cartography	pushbroom scanner 2 vis 10m x 10m 1 n-IR
MEOSS Germany and India	5 CCD arrays: 2 aft, 2 forward, 1 vertical, each with 2 vis resolution variable 1 n-IR 67 x 67m - 150m x 150m
MESSR Japan	2 CCD pushbroom scanners 2 vis 50m x 50m 2 n-IR
TERS: Tropical Earth Resources Satellite Indonesia/Netherlands earth resources	CCD 2 vis 20m x 20m 1 vis 10m x 10m 1 n-IR 20m x 20m 1 thermal IR(t-IR) 100m x 100m
Visible and thermal-IR Radiometer Japan Marine Observation	CCD 2 visible 900m x 900m 2 t - IR 2700m x 2700m
SISEX: Shuttle Imaging Spectrometer Experiment USA Shuttle	128 bands in range 0.4 - 2.5 µm 10nm interval 0.4 - 1.0 µm 20nm interval 1.0 - 2.5 µm 30m x 30m
STIMS USA Shuttle version of TIMS (table 1.3)	pushbroom scanner 6 t - IR 30m x 30m

Table 1.4 Satellite systems under design and/or development

Sensor details as available - scanner name and acronym - country of origin - purpose	Scanner details as available - mechanical/CCD array - wavebands
ASAS Advanced Solid State Array Spectroradiometer Modification of existing NASA (JSC) system to include a 512 x 32 CCD array	32 bands, each 14nm, in range 0.40 - 0.85 µm or 0.50 - 0.95 µm
AVIRIS Airborne Visible-Infrared Imaging Spectrometer JPL research instrument. Replacement for AIS (table 1.3).	224 bands in range 0.4 - 2.4 µm
CBML/CSIRO Carr Boyd Minerals Ltd/ Commonwealth Scientific and Industrial Research Organisation	prototype wavebands 3 visible 3 n-IR 4 m-IR 4 t-IR
Fluorescence Line Imager Moniteq for Canadian Fisheries/CCRS. programmable stereoscopic imaging system. 5 x 2 CCD array sensors	Choice of 256 channels, each 1.9nm in range 0.42 - 0.81 µm bands depend on configuration: i. Chlorophyll mapping ii. Fluorescence line properties
Multifads N2 Multispectral fast area digitising scanner	as Landsat MSS

Table 1.5 Airborne systems under design and development

systems, together with ground radiometer and spectrophotometer data and experience from the Landsat MSS have built up a reference bank of information on the spectral response of vegetated targets. This is used by expert panels such as NASA's Botanical Sciences team (see Slater, 1985), to define the optimum combination of wavebands for operational satellite sensors.

Imaging spectrometry is the simultaneous acquisition of images in many narrow contiguous spectral bands (NASA, 1984b) and is the logical extension of sensors such as the Daedalus series. It is typified by the NASA/Jet Propulsion Laboratory's AVIRIS programme (table 1.5) which replaces NASA's AIS mentioned earlier. The CCRS's FLI system (table 1.5), which allows a choice of 8 bands, each of 1.9nm width in the range 0.42µm to 0.81µm is an example of the specialised use of AIS.

NASA is pushing ahead with airborne trials of the AVIRIS system. Shuttle flights are planned for the SISEX sensor (table 1.4), culminating in an instrument such as the High Resolution Imaging Spectrometer on NASA's proposed polar orbiter, the Earth Observing System (NASA, 1984c). A continuous improvement in spectral resolution is therefore a major feature of the systems currently under design and development.

A second major theme is the use of linear and area detector arrays instead of mechanical scanners. The relative merits of the two designs are discussed more fully in chapter 2. In summary, the multiple array system has the capability for an improved radiometric sensitivity, and has fewer mechanical parts. Until recently the long wavelength cut-off of such charge-couple device (CCD) systems was constrained to 1.1µm. However SPOT 3 & 4, the next two systems in the SPOT programme will include a mid-IR band in the multispectral sensor.

Table 1.4 lists the spaceborne systems currently at the design stage. It is clear that a growing number of countries are involved in the development of satellite hardware, alone or in partnership. For most of these systems, the aim is to provide usable and appropriate information on national resources. They approximate, or improve slightly on the parameters of the MSS or the TM and the majority use MLA technology. The experimental Shuttle instruments, derived from airborne systems, demonstrate the scale and direction of future developments. These include a detailed treatment of the thermal IR by a CCD derivative of the Daedalus TIMS scanner, and the AIS experiments described above.

In summary, in both airborne and space systems, there is a move to finer spectral and spatial resolution, and a general increase in the use of multiple linear array technology. Following the success of the Landsat programme and its subsequent privatisation, there is an increased awareness of the need to be autonomous in the acquisition and processing of remotely sensed data and a number of countries are developing their own remote sensing hardware as part of a national space programme. These operational systems have features close to those of the Landsat MSS and TM sensors. Tables 1.4 and 1.5 predict the availability of a vast amount of information from experimental and operational systems in the 1990s and beyond.

In the immediate future however, the most important systems for earth resources will remain the two Landsat instruments and the French SPOT system. Within the considerations of spatial, spectral and temporal resolution this thesis therefore concentrates on these three systems.

1.5 The User Market

From the variety of system specifications given in tables 1.2 - 1.5, it is clear that the technology exists to build a satellite for almost any purpose. However the status of remote sensing depends as much on the response of the user community as it does on the space hardware and Holmes (1982) asserts that "we don't yet know how to string the technologies together to do jobs".

In Britain, this communications gap was also noted in the submission of the Remote Sensing Society to the House of Lords Select Committee on

Science and Technology (HMSO, 1984; Curran and Plummer, 1985). The evidence notes that "there is an inherent difficulty in integrating those who devise the technologies, and those that use them", mainly because the two groups work within two different scientific and career frameworks. A further comment from the Select Committee notes that "investment in the design and construction of platforms has not been matched by that in the development of operational techniques for using the data". The user community defines Holmes's "jobs" in terms of their own requirements for information, which may not be perceived or readily understood by the system designer. Henderson (1984) confirms this and suggests that even in the field of exploration geology, where remote sensing is used operationally, the remote sensing market must be developed further before it becomes a profitable operation.

In Britain, the majority of work in the remote sensing of natural resources is carried out in the research environment. Although most examples deal with real management problems as case studies, the results are not generally followed up once the research project is complete.

The basic concepts of remote sensing are similar to those of any technique which describes a distribution of cases by one or more variables and seeks to group those cases which have a similar pattern of attributes. The problems arise in the expression and phrasing of these concepts in each discipline. Again this problem is recognised in Britain and backed in practical terms by, for example, the National Remote Sensing Centre's Roadshow which is part of a campaign to promote the knowledge and use of remote sensing at all levels.

The applied use of remote sensing is identified as an important theme of this thesis. As noted previously, the work was developed in close collaboration with staff of the North Yorks Moors National Park. The technique was considered by the National Park to hold considerable promise, and work is continuing on its detailed application to specific management problems.

Chapter Two: The sensor systems.

2.1 Introduction

As discussed in chapter 1, the interpretation of remotely sensed data is based on the fact that targets can be isolated from each other by differences in their spectral response. Analysis of the data by eye or machine therefore concentrates on detecting change in radiance across an image and matching it to patterns of interest at the ground.

The validity of this approach depends on the accuracy of two assumptions. The first is that at least some of the wavebands recorded are measuring features of the target which are meaningful to the interpreter. The second is that a density change in the image is a faithful record of change in spectral radiance at the ground. This chapter examines the truth of these two assumptions for the Landsat MSS and TM and the SPOT HRV sensors, and, where appropriate, the Daedalus AADS1268 scanner.

Sections 2.2 and 2.3 are a brief introduction to the sensors and to the practical effects of the interdependence between spatial, spectral and radiometric resolution. The characteristics of the sensors are summarised in tables 2.1 and 2.2 and further details can be found in the references given with these tables. The accuracy of airborne data as simulations of satellite sensors has been examined in some detail, notably by Saint and Weill, (1984) and Price, (1986) in connection with the U.S.A. SPOT simulation programme. The ATM data analysed in chapters 5, 6 and 7 are uncorrected from their raw state; they therefore mimic the appopriate satellite data only in their bandwidths. Table 2.1a lists the parameters of the airborne scanner data and individual sorties which must be corrected to those of the satellite sensor if a true simulation is required. Table 2.1b lists the actual parameters, as available, for the Daedalus data used in this thesis. It was not possible to collect sufficient ground data to give an accurate estimate of the effects of atmospheric distortion, nor were the data corrected radiometrically or converted to the absolute scale

Parameters of scanner and scanner data

1. Noise equivalent radiance and signal to noise ratio
2. Point spread function
3. Shape of sensor transmission curve
4. Look angle and pixel size across swath
5. Overlap between scan lines
6. Signal digitisation error
7. Bandwidths
8. Data should be converted from relative DN to absolute radiance and corrected for 'limb brightening'

Parameters of flight

1. Time of day (c. 9.30 am for Landsat)
2. Flight direction (N-S for Landsat and SPOT)
3. Atmospheric variables should be recorded to enable atmospheric correction

Table 2.1a Parameters of the airborne scanner data and individual sorties which must be corrected to those of the satellite sensor system if a true simulation is required.

	time GMT	flying height m	ground speed kts	pixel size m	flight direc.
Airborne Thematic Mapper (ATM) - chapters 5 & 6					
Acquired 7.9.83	13:37 - 15:39	677	140	1.4 x 1.3	N-S
Acquired 24.5.84	11:32 - 12:05	1980	175	4.0 x 3.0	N-S
Acquired 31.8.84	16:08 - 16:36	2010	150	7.0 x 3.0	N-S
Airborne SPOT HRV - chapter 7					
Acquired 14.5.84	11:17 - 11:26	7000	250	15.0 x 12.0	N-S
Acquired 7.7.84	c.15:00	c.4000	200	10.0 x 8.0	N-S

Table 2.1b Known parameters of airborne scanner sorties

of radiance. More recent work arising from these simulation campaigns has however stressed the need for such systematic correction and suggested ways in which this can be done (see, for example, Donoghue and Hook, 1986; Wilson, 1986)

The discrepancies between the two types of data therefore precludes direct prediction of the utility of satellite sensor data from the analyses presented in this thesis. It is however the satellite sensor data that the National Park authorities are interested in, as regular acquisition of airborne scanner data is not an attractive option (mainly due to the data handling problems outlined above). The airborne scanner data are analysed in the absence of the desired satellite sensor imagery; the analysis therefore concentrates on the pattern of response returned from the moorland vegetation in wavebands which approximate those of the Landsat MSS and TM and the SPOT HRV sensors. The results suggest that, when available, it will be worthwhile for the National Park to invest in a more rigorous analysis of the satellite sensor data. The remainder of this chapter therefore concentrates on the characteristics of the satellite sensor systems

Section 2.4 compares the spectral characteristics of the sensors to the spectral response of vegetated canopies. Section 2.5 examines sources of noise in the sensors and the sensing process and their effect on interpretation of the data. Together they give an estimate, for each sensor, of the reliability with which pattern in spectral response, as apparent in the data, can be interpreted as pattern or change in vegetated targets at the ground. A more general treatment can be found in Curran and Hay (1986).

2.2 The sensor systems.

All imaging sensors record energy from a discrete ground area and focus it onto a detector which is sensitive to energy at certain wavelengths. An electrical signal is output from the detector in response to the energy

Band Name	Purpose/targets	Limits in µm	NEΔR / NEΔT	Number of detectors (with type & material where available)	References
MSS 4 (1)●	Movement of sediment laden water, shallow water delineation.	0.50 - 0.60	0.57 %	6 photomultiplier tubes	Thomson 1981 Salomonson & Park 1979
MSS 5 (2)	Emphasises cultural features	0.60 - 0.70	0.57 %	6 photomultiplier tubes	Salomonson et al. 1980
MSS 6 (3)	Vegetation, boundaries between wet and dry areas	0.70 - 0.80	0.65 %	6 photomultiplier tubes	
MSS 7 (4)	As MSS 6 with haze penetration	0.80 - 1.10	0.70 %	6 silicon photodioes	
TM 1	Coastal water mapping, soil/vegetation & deciduous/coniferous differentiation	0.45 - 0.52	0.80 %	16 silicon	USGS 1984 Blanchard & Weinstein
TM 2	Health in vegetation	0.52 - 0.60	0.50 %	photomultipliers	1980
TM 3	Plant species differentiation	0.63 - 0.69	0.50 %		
TM 4	Biomass survey; water body delineation	0.76 - 0.90	0.50 %		
TM 5	Vegetation moisture; differentiation of snow and cloud	1.55 - 1.75	1.00 %	16 Indium antimonide	
TM 7	Hydrothermal mapping	2.08 - 2.55	2.4 %	photoconductors	
TM 6	Plant heat stress measurement, other thermal mapping	10.40 - 12.50	0.5 K	4 mercury cadmium telluride (HgCdTe)	
XS 1	Vegetation. Turbidity assessment and bathymetry	0.50 - 0.59	0.5 % at nadir 0.5 (1 + α) %	3000 pairs of CCDs in each band	Midan 1986 Chevreal et al. 1981
XS 2	Chlorophyll dependent features of vegetation. Bare soils and rocky surfaces.	0.61 - 0.68	α = 0.4 or 0.7 elsewhere dept.		
XS 3	Best atmospheric transmittance. Biomass, water bodies	0.79 - 0.89	on scan posn.		
ATM 2	simulation of TM 1	0.45 - 0.52	< 0.10 %	1 per band silicon	
ATM 3	simulation of TM 2	0.52 - 0.60	< 0.10 %		
ATM 5	simulation of TM 3	0.63 - 0.69	< 0.06 %		
ATM 7	simulation of TM 4	0.76 - 0.90	< 0.15 %		
ATM 9	simulation of TM 5	1.55 - 1.75	< 0.30%	1 indium antimonide	
ATM 10	simulation of TM 7	2.08 - 2.35	< 0.70 %		
ATM 11	simulation of TM 6	10.40 - 12.50	< 0.2°C	1 HgCdTe	

● no.s in brackets refer to band names of MSS instrument on Landsats 4 & 5

Table 2.1 The spectral and radiometric characteristics of the Landsat MSS Landsat TM, SPOT HRV and Daedalus airborne scanner sensors

Sensor and platform	Spatial resolution	Pointing accuracy	Orbit / repeat cycle	Band to band registration / References
Landsat MSS on Landsats 1 - 3	79m x 79m IFOV 56m x 79m IFOV/ sample rate 86 urad at detector 1 active scan	pitch: < +/- 0.7° yaw: < +/- 1.0° roll: maxm. angular displacement +/- 1.0° angular rate of change < 0.04° s^{-1} Attitude measurement: pitch & roll measured to +/- 0.07°	swath = 185 km 18 day repeat cycle 37 km repeat accuracy adjacent tracks imaged on consec- utive days, with 34% sidelap at 40°.	0.25 pixel Slater 1980 Landsat Data Users Notes (NASA) Simonett 1983
Landsat TM on Landsats 4 & 5	30m x 30m point spread funcn. 42 urad at detector 2 active scans	attitude control pitch: 0.01° yaw: 0.01° roll: 0.01° angular rate of change 10^{-6} s^{-1}	swath = 185 km 16 day repeat cycle adjacent tracks imaged 7 days apart with 20% sidelap at 40°.	0.3 pixel over 90% of data Salomonson <u>et al</u>. 1980 USGS 1984
SPOT HRV multi-spectral mode	20m x 20m IFOV 2 x 13 = 26 urad at detector no scan	attitude control: angular velocities pitch: 1.5 x 10^{-4} yaw: 5.0 x 10^{-4} roll: 3.0 x 10^{-4} off nadir pointing accuracy 4 x 10^{-4} rad any position +/- 27°	Each instrument: swath=60km 2 instruments in combi tion max. = 117km (nadir) - 150 km (extreme). 26 day repeat cycle reduced by off-nadir capability 5 km repeat accuracy	0.2 - 0.3 pixel CNES unpub. Chevrel <u>et al</u>. 1981

Table 2.2 Orbital characteristics and spatial resolution of the Landsat MSS, Landsat TM and SPOT HRV sensors.

incident upon it. The signal is sampled, transmitted to a ground station and processed. Successive samples and signals build up a grid of contiguous picture elements into an image. The size of the ground cell that is sensed is defined by the optics and the orbit of the system.

Passive imaging sensors can be classified by the way in which they capture data. The three most common groups are frame sensors such as the RBV camera on Landsats 1-3, mechanical scanners and linear array or pushbroom scanners (Norwood and Lansing, 1983).

The Landsat MSS and TM are mechanical scanners in which a flat mirror scans across the satellite track and reflects each part of the swath in turn through a telescope lens system and onto the detectors. The forward movement of the spacecraft provides the second, along track, dimension in the imagery. The mirror scan rate and spacecraft velocity are adjusted so that successive mirror scans view contiguous ground segments, and the final image is continuous. The working and layout of the MSS and TM, and the airborne AADS1268 system are shown in figure 2.1.

The SPOT HRV sensor is a pushbroom scanner. Each part of the ground across the satellite track is imaged simultaneously onto a rank or array of CCD detectors. The layout of the system is summarised in figure 2.1. Push-broom sensors have the advantage of a long dwell time and no moving parts, but calibration is difficult because of the large number of detectors in the array. Table 2.3 summarises the relative merits of pushbroom and mechanical scanners. Section 1.4.2 in the previous chapter noted that linear array technology is gaining rapid popularity over conventional mechanical scanners. This was reflected in the pressure for a pushbroom alternative to the present TM sensor (Colvocoresses, 1977, 1979).

2.3 The interdependence of spatial, spectral and radiometric resolution in system design and data interpretation.

The aim of this thesis is to define the importance of spectral, spatial and temporal resolution as characteristics of remotely sensed data for use

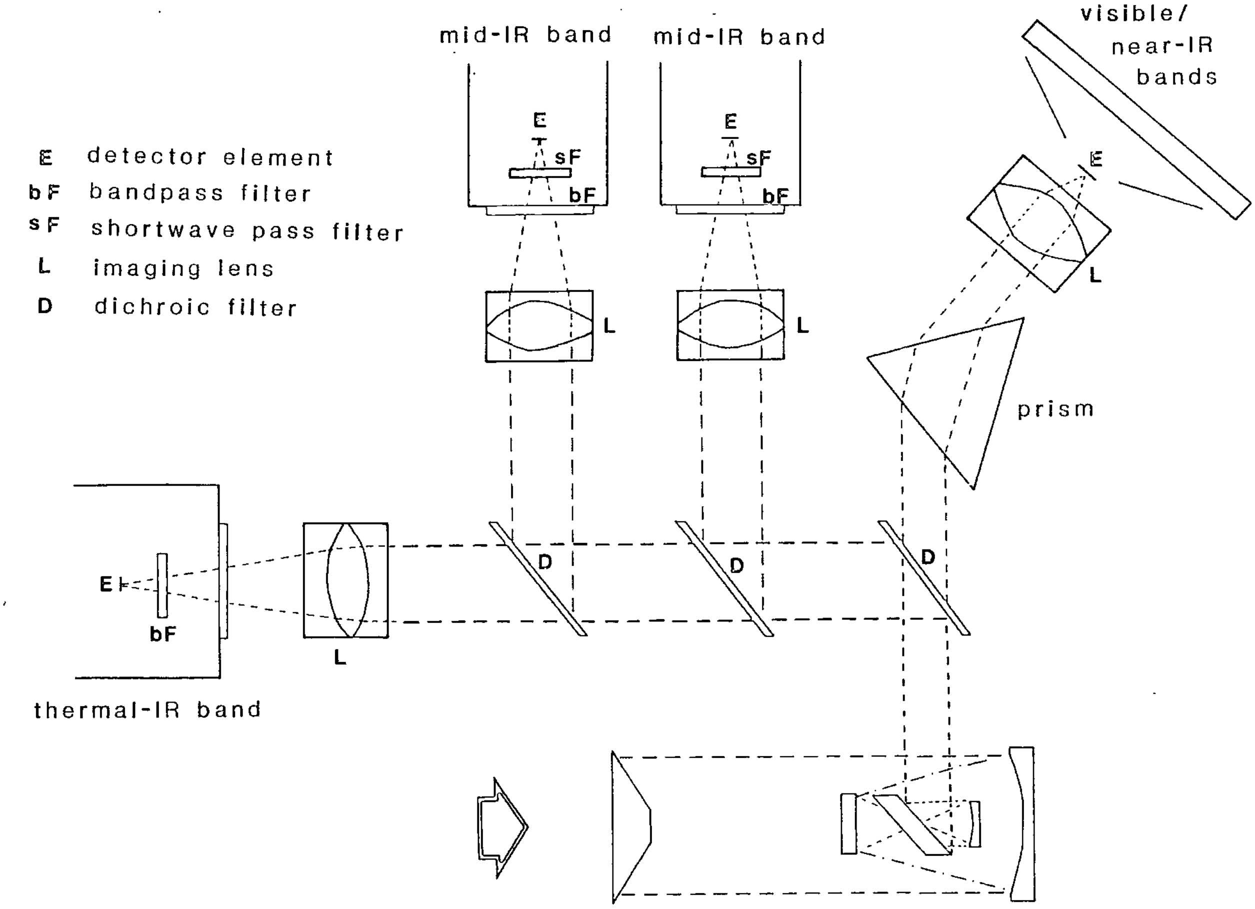


Figure 2.1a Daedalus AADS 1268 system optics schematic

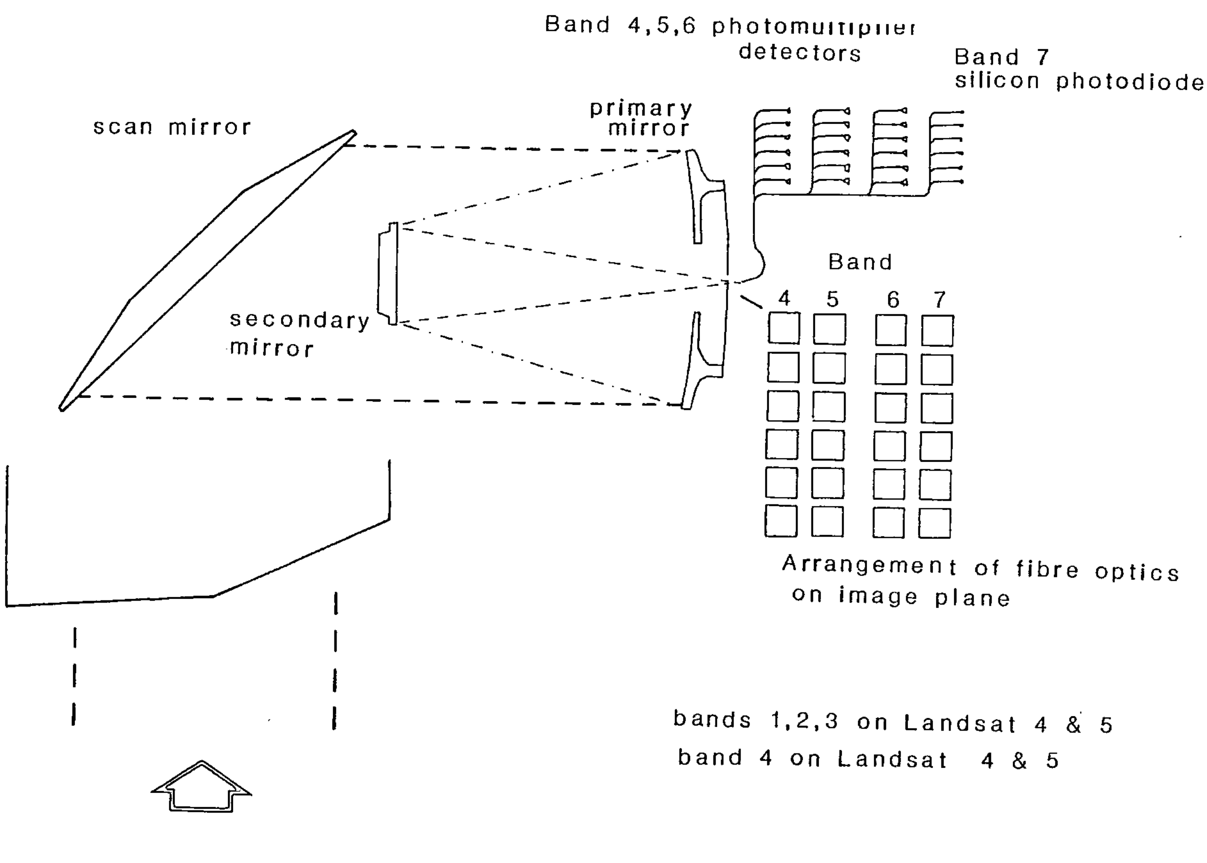


Figure2.1b Landsat MSS optics schematic

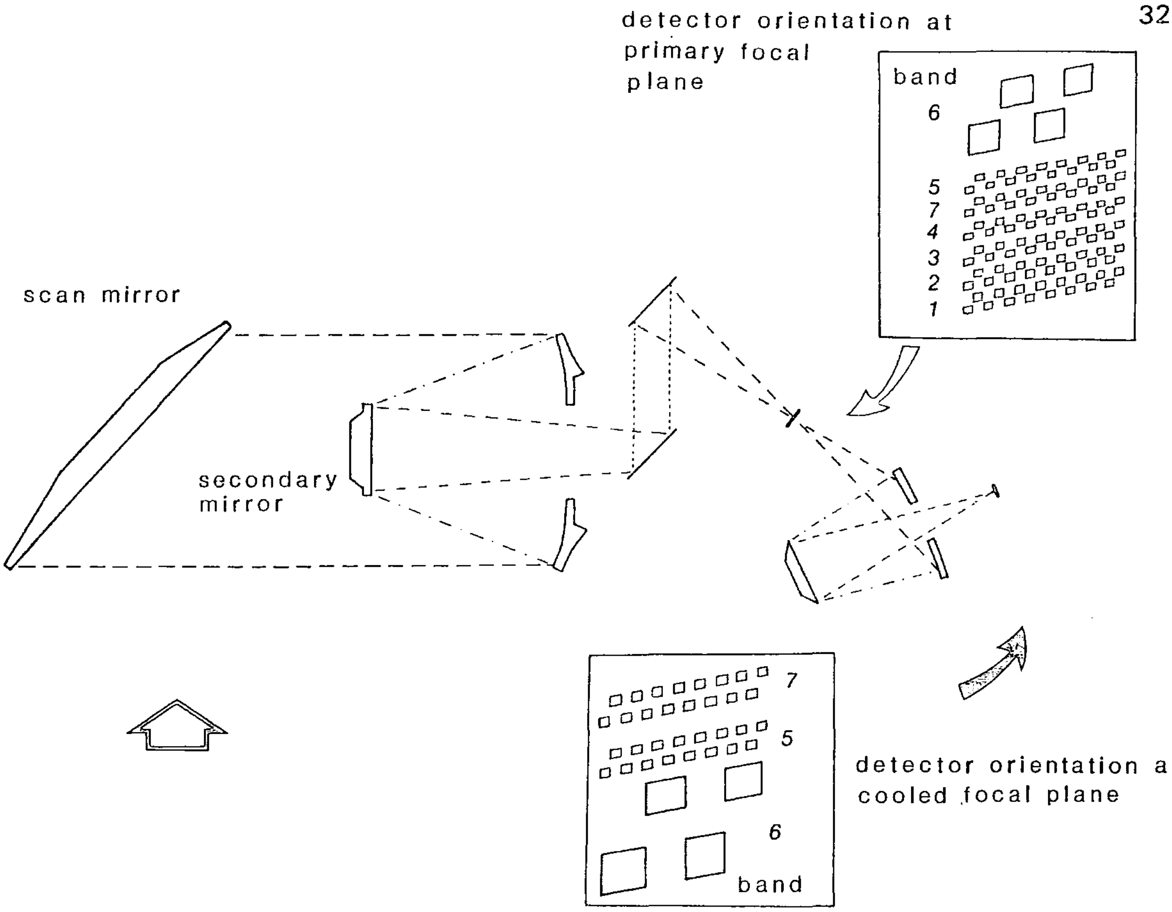


Figure 2.1c Landsat TM optics schematic

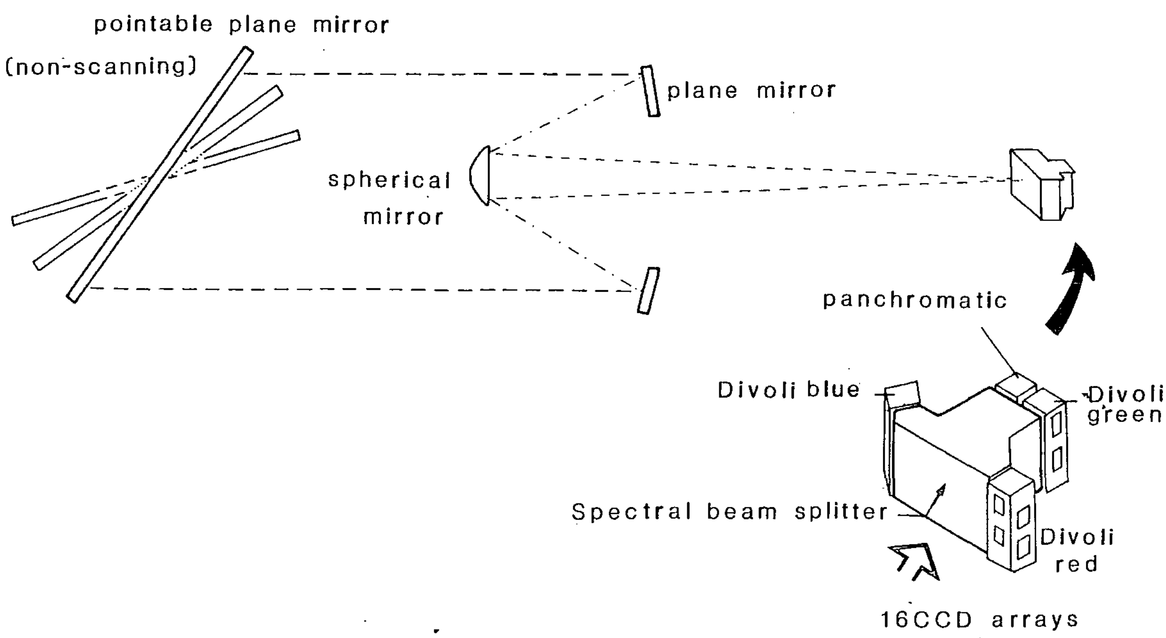


Figure 2.1d SPOT HRV optics schematic

NB Figures 2.1a - 2.1d not to scale or exact orientation

ADVANTAGES of pushbroom scanners

i. Lighter weight and smaller size
ii. Lower power requirement and longer life expectancy
iii. No moving parts, greater stability
iv. Higher geometric and radiometric accuracy
v. Higher SNR
vi. Lower cost

DISADVANTAGES of pushbroom scanners

i. Higher number of detectors to calibrate

Table 2.3 Comparison of a pushbroom and a whiskbroom (mechanical) scanner. from Curran (1985) and Slater (1980).

in the moorland environment. As noted in chapter 1, the resolution parameters of a sensor interact with each other and with the spectral and spatial characteristics of the target. This section gives a more detailed outline of the effects of this dependence on the design of the system and the quality of the data.

The fundamental control on the selection of resolution parameters in system design is the absolute amount of radiant flux that reaches the detectors. A part of the signal output from the sensor is inherent random fluctuation or noise from the detector itself (see section 2.5.2). If variation in the incoming radiation is to be recorded reliably then the amount of incoming radiation must be considerably greater than this noise level.

If spectral resolution is held constant and the spatial resolution is increased, then energy is gathered from a smaller area on the ground and the radiant flux at the detector is decreased. If spatial resolution is held constant but a broad visible waveband is divided into its blue, green and red components, the total energy reaching the detector in each waveband is also reduced. Spectral and spatial resolution therefore fix the absolute amount of energy which reaches the detector.

The radiant flux at the detector and the detector noise level determine the sensor's radiometric resolution or the maximum number of quantization levels that the sensor's output can be digitised to. The value of each quantization step must be above the amount of incoming radiation needed to match the inherent detector noise (the Noise Equivalent Radiance or NER, more often expressed as the Noise Equivalent Reflectance Difference NEΔR or Noise Equivalent Temperature Difference NEΔT). The maximum number of quantization levels is the number of such steps which can be fitted into the radiometric range (the range of radiance values at the sensor aperture). The orbital characteristics that are needed to maintain the design signal to noise ratio (SNR) for a given spatial and spectral configuration can be a constraint on the temporal resolution of the system.

The spatial resolution of a system is defined physically by the angular field of view subtended by a detector element, projected from the nominal platform height to its spatial expression at the ground. However, as noted in chapter 1, an object of high contrast with its background will alter the radiance of the pixel in which it falls and surrounding pixels so that it is visible while still below the stated resolution. Thus roads and rivers less than 79m wide can be traced on Landsat MSS imagery. Conversely, the equivalent photographic resolution for a target of low to medium contrast with its surroundings is in the order of 200-250m (Forshaw et al., 1983; Townshend, 1981b).

A number of definitions of spatial resolution have been derived from photogrammetry and electronic engineering to allow for this dependency on spectral response. The essence of these measurements is that the spatial resolution of a system is not completely defined by the physical IFOV of the sensor but varies with the spectral characteristics of the target and the parameters of the sensor. Table 2.4 lists a number of alternative definitions and they are discussed further by Townshend (1981b) and Forshaw et al. (1983).

Intuitively it is desirable to maximise all resolution parameters. This is not technically possible within a budget and the interaction between all parameters means that they must be considered together. Further, beyond a certain point the growth in benefit from increasing resolution starts to decrease and eventually to level off (fig. 2.2). There is therefore an optimum resolution for each parameter, for each application, above which the cost of building the system and analysing the data surpass the increase in the value of the information gained. Figure 2.3 outlines how these perceived optima vary for different applications.

This thesis aims to define the optimal spatial and spectral resolution of data for each stage in the multi-level management problem of mapping and monitoring moorland vegetation. As noted in chapter one the requirements for each task are unlikely to be met from a single system. A GIS approach

1. Geometrical properties of the imaging system
   example: INSTANTANEOUS FIELD OF VIEW (IFOV). The angular subtense of the detector

2. Ability to distinguish between two point targets
   example: RAYLEIGH CRITERION. The criterion states that two equal intensity sources are just resolved if the peak of the image of one source lies on the first zero of intensity of the image of the second source. (The image of each source is a diffraction pattern consisting of a central maximum surrounded by alternate light and dark zones.)

3. Ability to measure extent of small but finite targets
   example: EFFECTIVE RESOLUTION ELEMENT (ERE). The area of an object for which the relative spectral parameters of its central point can be assigned with 95% confidence that they differ no more than 5% from the actual parameters, given a spectral contrast of 30% of the possible range between the object and its surroundings.

4. Ability to measure periodicity of repetitive targets
   example: LINE PAIRS/MM. The maximum number of pairs of alternating black lines and white spaces over a given distance where sufficient contrast remains for the lines to be resolved. Used to define the modulation transfer function (MTF) of sensor components.

Table 2.4 Alternative definitions of spatial resolution.
summarised from Forshaw et. al. (1983) and Slater (1980).

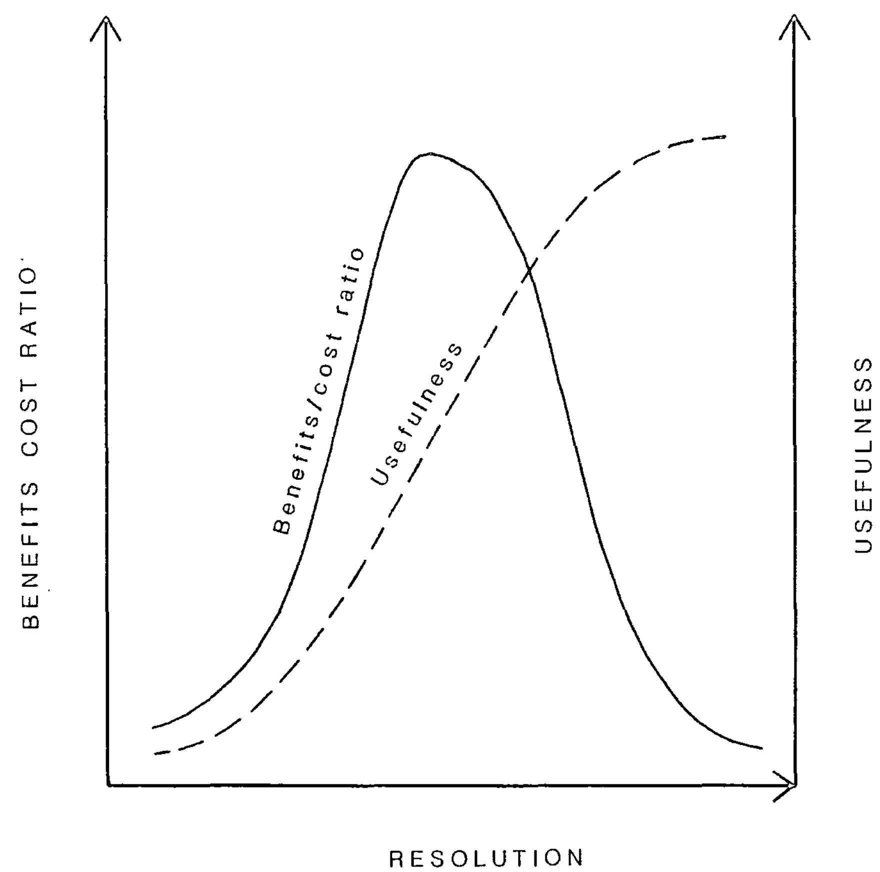


Figure 2.2 Relationship between data usefulness, benefit/cost ratio and sensor resolution (spatial, spectral, radiometric or temporal). From Slater (1980).

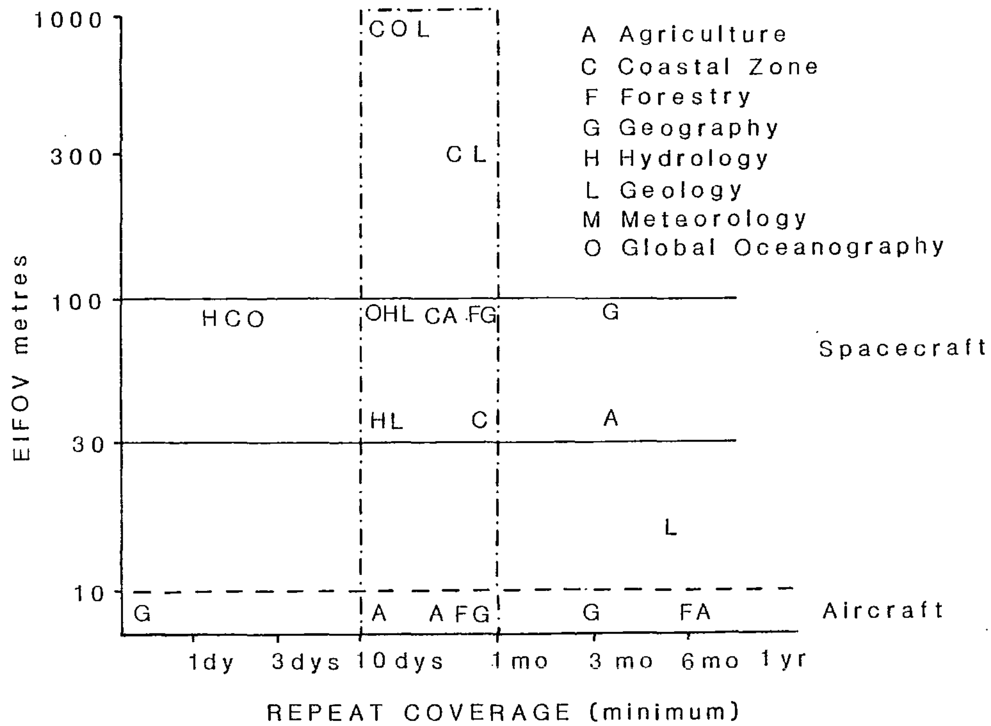


Figure 2.3a User requirements for repeat coverage and spatial resolution, quoted as effective instantaneous field of view (EIFOV). From Slater (1980).

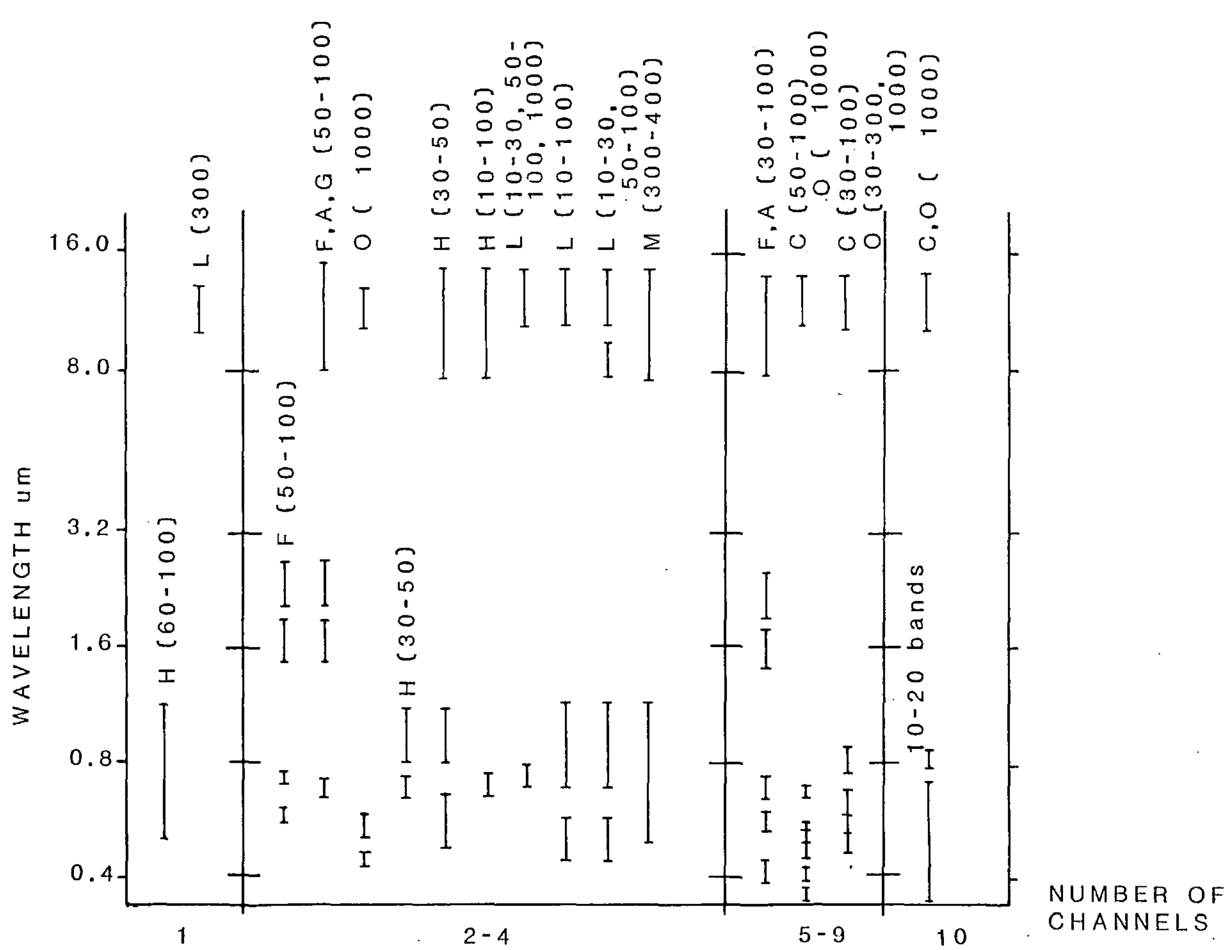


Figure 2.3b User requirements for spectral data. Figures in brackets are range of required spatial resolutions (as EIFOV). Most users want a combination of visible and near-IR and temporal IR wavebands, but a range of specialized sensors would be needed to satisfy all requirements. From Slater (1980).

mimics an optimal sensor by combining the best subsets of the available data in a spatially referenced system.

2.4 Spectral resolution of the Landsat TM, MSS and SPOT HRV sensors.

2.4.1 Factors affecting radiation from vegetated canopies.

The incoming radiation which falls on a canopy component is absorbed, transmitted or reflected. Remote sensing systems measure the amount which is reflected or absorbed and re-emitted as energy of a different wavelength. Figure 2.4 shows the relationship between absorption, reflectance and transmittance across the visible and near- to mid-IR wavelengths for healthy green vegetation.

At the upper boundary of the canopy, incoming radiation is the total solar irradiation. For components within the canopy it is the remaining direct flux, redirected flux from the surrounding components and diffuse flux from transmission through the intervening components. It therefore varies in amount and spectral composition.

If useful information is to be extracted from remote sensing data the image must be acquired in wavelengths where the canopy's radiance is controlled by features of the vegetation which are important discriminators in management terms. The factors affecting the spectral response of green vegetation are outlined below and reviewed comprehensively in Ferns and Barber (1981) and Wardley and Milton (1985). Recent contributions to the literature include Ripple (1985a, 1985b, 1986), Sellers (1985) and Everitt et al. (1985).

In the visible wavelengths (figure 2.4), the majority of incident radiation is absorbed. The main control on the amount and selectivity of absorption is the type and amount of pigmentation present in the canopy element. Chlorophyll a and b absorb 70 - 90% of available light in the blue (c. 0.45μm) and red (c. 0.65μm) parts of the spectrum and this is used as the energy source for photosynthesis (Gausman, 1974). Carotenoid and anthocyanin pigments also absorb strongly in the blue wavebands (Ferns

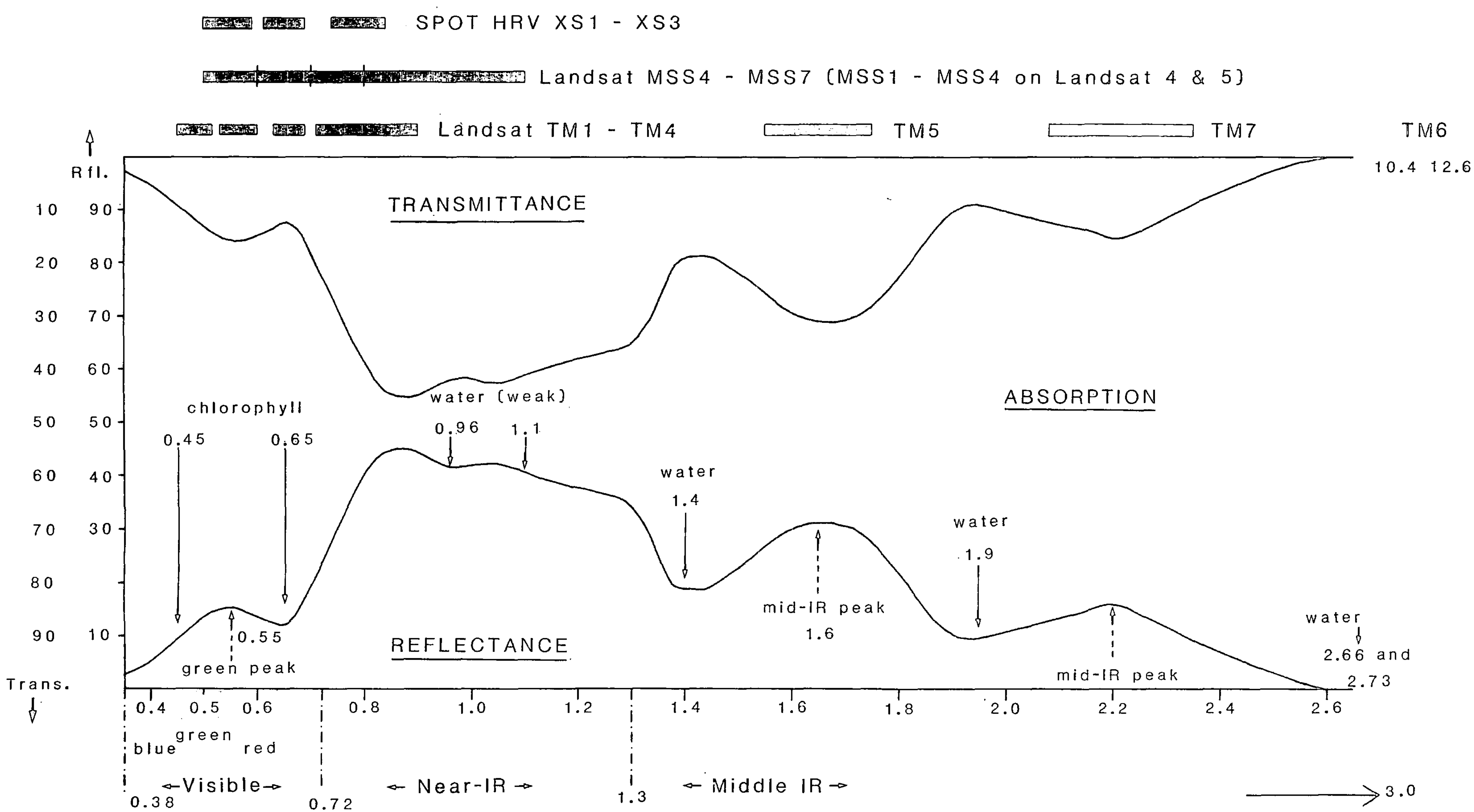


Figure 2.4 Relationship between transmittance, reflectance and absorption from visible to thermal-IR bands. After Ferns and Barber (1981) and Simonett (1983).

and Barber, 1981). Absorption by all pigments is smallest at about 0.55µm which gives a local peak of approximately 15% reflectance in the green wavelengths (Gausman, 1982).

The near-IR is a region of low absorption, high transmission and high reflection of incoming radiation. The near-IR wavelengths are reflected or scattered by passage from a medium to one with a dissimilar refractive index (RI). The most important of these boundaries is at the cell wall/air space interface in the palisade and lower mesophyll layers of the leaf. The total near-IR radiance of a leaf is made up of reflection and refraction at these boundaries and to a lesser extent at the discontinuities within the cell (Ferns and Barber, 1981; Knipling, 1970). The amount of near-IR light reflected from a healthy mature leaf is therefore roughly proportional to cell density and depends on maintenance of the RI discontinuity by continued hydration of the cell walls.

In the mid-IR, the spectral response of vegetation is dominated by strong water absorption bands at approximately 1.4µm, 1.9µm and 2.7µm, with minor ones at 0.96um and 1.1um (Tucker, 1980a). The amount of radiance in these wavebands is inversely related to the total moisture content of the leaf (figure 2.5). The regions of maximum absorption by water are avoided by remote sensing systems because of their sensitivity to the moisture content of the atmosphere. The mid-IR bands of the TM (TM5: 1.55-1.75µm and TM7: 2.08-2.35µm) are located between local absorption maxima. However the former was included specifically to detect drought and water stress in plants (Salomonson and Park, 1979) and both are identified by Tucker (1980a) as regions most sensitive to changes in leaf water content. Swain and Davis (1978) suggest a "carryover" effect to explain the high dependence on moisture content throughout the mid-IR. Work by Knipling (1970) suggests that in the absence of strong water absorption the interaction of these wavelengths with vegetation is not different from that in the near-IR.

In the thermal IR the radiance measured by a remote sensing system is made

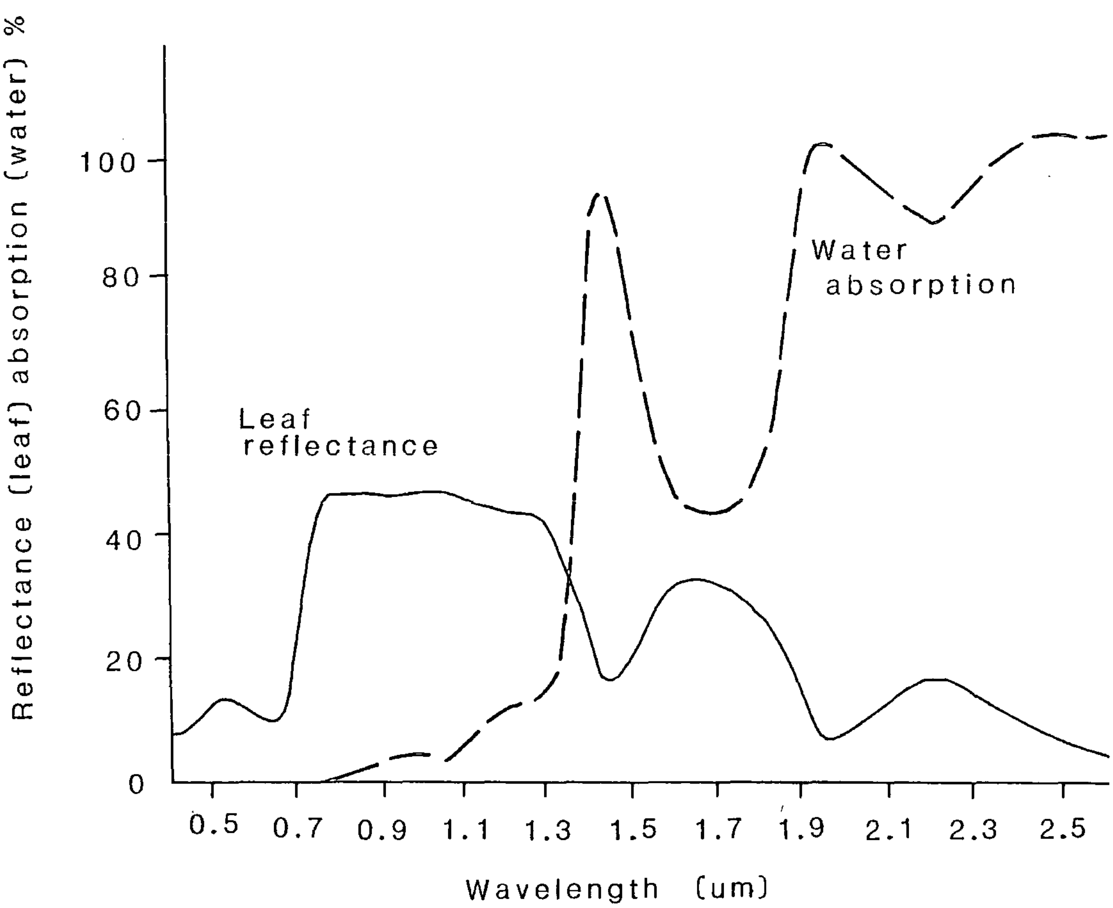


Figure 2.5 The inverse relationship between leaf reflectance and water absorption. The water absorption curve repents the amount of absorption caused by a layer of water lmm deep. From Swain and Davis (1978)

up almost completely of emitted flux. The amount of radiation depends on the canopy's absolute temperature and its emissivity. Canopy temperature is determined by the energy budget of the plant or leaf and the proportion of energy which is reradiated by conduction or convection or through latent heat transfer during transpiration (Puritch, 1981; Gates et al., 1965). These metabolic functions are complexly inter-related and are strongly affected by environmental conditions, as is the mechanical removal of heat. The Landsat TM is the first sensor to acquire thermal data at a spatial resolution (120m x 120m) which is relevant to routine natural vegetation monitoring. The MSS on Landsat 3 carried a little-used thermal channel which had a nominal spatial resolution of 237m x 237m (see Price, 1981). The thermal band on the AVHRR instrument of the NOAA meteorological series has a spatial resolution of 1100m x 1100m. The weak emitted flux at the thermal IR wavelengths and the relatively poor sensitivity and stability of thermal detectors continue to place limits on the resolving power of civilian thermal sensors.

The outline above implies that a change in radiance can be traced directly to change in a single specific feature of the canopy element. However the relationships described above are derived mostly from laboratory experiments which measure the hemispherical reflectance of individual canopy components under controlled conditions. The directional response of a living vegetated canopy is more complex, as the canopy is a "not a large leaf, but a mosaic of leaves, other plant structures, background and shadow" (Curran, 1983). In addition the incoming irradiance is not constant in amount or spectral composition. A change in radiance may therefore have a number of causes (Curran, 1980, 1983).

A low red radiance means that the majority of light in the red wavelengths is being absorbed. This can be caused by an increased concentration of chlorophyll, a high productivity during peak growth or an increase in the amount of green leaf material. A dark peat substrate will also absorb light in the visible wavebands (Curran 1983) to mimic any of these factors. The breakdown of chlorophyll which accompanies senescence increases red reflectance in a similar way to a reduction in vegetation cover.

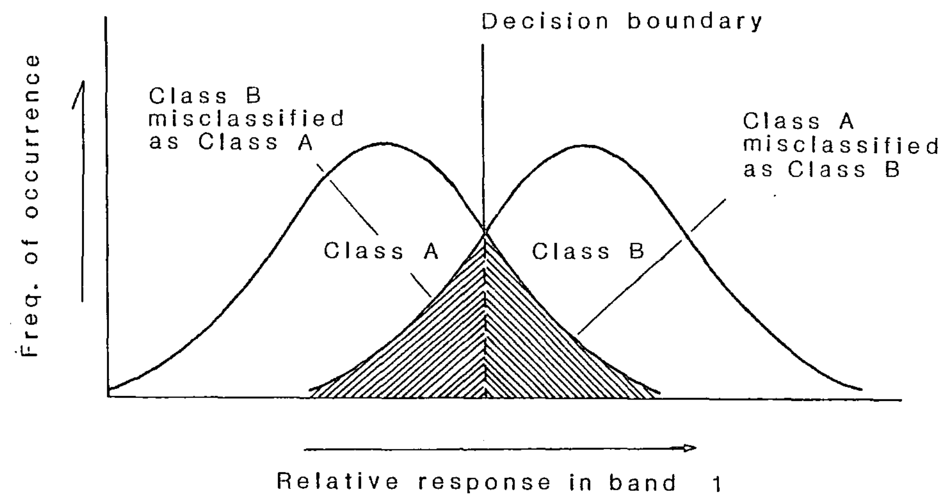
Near-IR radiance is also related to the phenology and physiology of the plant. A young leaf has densely packed cells and therefore has a relatively low response in the near-IR. A leaf under stress, where the cell walls are dehydrated or broken down, may have a similarly low response. A mature, healthy leaf of the same species which has an open structure will have a higher response (Gausman, 1974). Given stress free stands of uniform age the near-IR can also separate different vegetation types as leaf structure varies from species to species.

Thus a variety of canopies can have a similar response in one waveband and vice versa. This is particularly true for natural vegetation where stands vary in structure and specific composition even within one cover type and different stands may show different degrees of phenological change. Thus a single waveband at a single date is unlikely to discriminate between all components of a naturally vegetated target and the discrimination that is possible will be somewhat unpredictable.

As the controls on radiance are different for adjoining parts of the spectrum a careful selection of wavebands should provide a series of independent information sources on the characteristics of a vegetated area and thus allow discrimination between its components (fig 2.6). In practice the features of plant physiology and metabolism which control spectral radiance are interdependent so that wavebands in different spectral regions will retain some redundant information. However a higher spectral discrimination is expected where several spectral regions are measured separately. This suggestion forms the basis of analysis of chapter 5 and is discussed further there.

2.4.2 Sensor bandwidths

Figure 2.4 shows the position of the nominal wavebands on the Landsat MSS



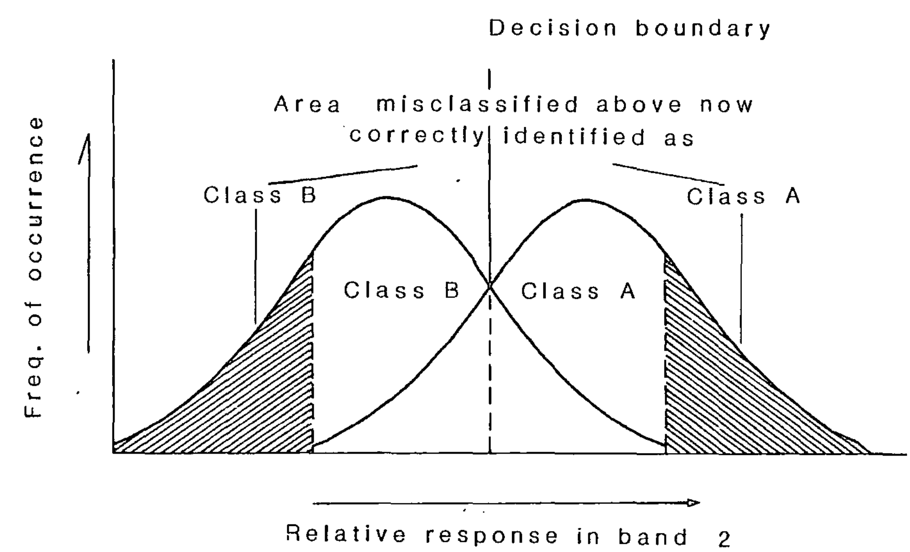


Figure 2.6 Improving recognition of cover types by using different wavebands. In this case there is a spectral reversal between the two bands. Neither class can be separated in either band alone but the areas of spectral overlap in band 1 are clearly separable in band 2. All elements of the two classes will be recognised correctly if both bands are used. After Swain and Davis (1978).

and TM and the multi-spectral configuration of the SPOT HRV sensor in relation to the major controls on spectral response. The reasons for the choice of each waveband at the system design stage are given in table 2.2. The matching of the response of individual detectors and the correspondence between actual and nominal bandwidths are discussed in greater detail in section 2.4.4.

All three satellite systems have wavebands in the green, red and near-IR wavelengths, identified by Tucker and Maxwell (1976) and Tucker (1978) as the critical regions for vegetation monitoring. There are however considerable differences between the systems in the location of the upper and lower cut-offs of each band. This section examines the precise location of each waveband in relation to the response of green vegetation outlined in section 2.4.1. Ideally, the spectral response of a canopy in the wavebands of these sensors is expected to be a clear indicator of canopy identity or condition. The limits of each waveband should therefore fall within the wavelengths where spectral response is controlled by a single and known feature of the canopy.

There are some technical restrictions on the location of wavebands. The spacing of the green and red wavebands on the SPOT HRV is partly a function of the 20nm separation required between bands by the dichroic beam splitter (Chevrel et al., 1981). The original design recommendations for the Landsat MSS specified only band centres at 0.55μm, 0.65μm and 0.75μm, with "whatever can be acquired in the 0.8μm plus region" (Freden and Gordon, 1983). The actual bandwidths were the result of engineering constraints. Thus their limits appear "rather strange" to Tucker (1978).

The slight lessening of absorption in the green wavelengths causes a local peak in reflectance which is centred at about 0.55μm. The green band of a remote sensing system should therefore have a peak responsivity at 0.55μm. The adjacent red and blue wavelengths are absorbed strongly by plant pigments and the blue wavelengths are also susceptible to molecular scattering (Begni, 1982). The response to shorter wavelengths in particular should therefore be minimised as far as possible.

Horler et al. (1983) noted the existence of a "green edge" at about 0.52µm. The edge is the wavelength of maximum slope at the boundary between blue absorption and green reflectance and its exact position depends on the chlorophyll content of the leaf. The green wavebands of the SPOT HRV and Landsat MSS sensors (0.50-0.59µm and 0.50-0.60µm respectively) straddle the green edge at their lower limit and include some elements of the highly absorbent blue wavelengths. The green TM band (0.52-0.60µm) is a closer match to the local reflectance maximum.

At the upper limit of the green wavelengths at around 0.60µm reflectance and absorption reverse dominance over a wide wavelength interval (figure 2.4). There is no clear edge effect as at the blue/green interface and the positioning of the upper bound of the green band is therefore less critical.

The area of maximum sensitivity to chlorophyll absorption is 0.63- 0.69µm. The MSS red band (0.6-0.7µm) includes the less sensitive 0.60-0.63µm area but this is not expected to degrade the response. Tucker and Maxwell (1976) note that MSS band 5 (red) is well situated for biological remote sensing but Tucker (1978) later states that the band could benefit from removal of the 0.60- 0.63µm zone. In experimental data he found that the improvement this brought was more important for heterogeneous canopies, similar to those found in natural or semi-natural vegetation, than for simple, homogenous canopies more analogous to agricultural targets.

Both TM3 (0.63 - 0.69µm) and SPOT XS2 (0.615 - 0.68µm) are a good match to the peak absorption of chlorophyll. They are therefore expected to show a better correlation than the MSS band with chlorophyll dependent features of vegetation.

The transitions between blue, red and green wavelengths are local reversals in reflectance within the main control on reflectance in the visible bands which is the strong absorption by plant pigments. In the near-IR bands the dominant process is reflectance and this is controlled by the structure of the leaf and the canopy. Tucker and Maxwell (1976) identified 0.70-0.74μm as the zone of transition at the red/IR interface and found little or no relationship between grass canopy variables and radiance in this area.

Ferns et al. (1983), Horler et al. (1983) and Schutt et al. (1984) have investigated the behaviour of this transitional spectral region in some detail. They found that the position of the maximum rate of change in reflectance, or the "red edge" depends on chlorophyll concentration in a similar way to the green edge described earlier. The red edge can be located accurately in systems with narrow (<10nm) spectral bands. In most cases however it is more important to make a clear distinction between the absorptive and reflective parts of the spectrum. This is particularly true where IR:red ratios are used routinely in vegetation monitoring.

The Landsat MSS bands are not well placed to make such a distinction. The upper bandpass of MSS 5 (0.6-0.7μm) verges on the .70-.74μm transition zone identified by Tucker. This is important as it is relatively easy to block out lower wavelengths from a specified waveband, but considerably harder to define an absolute upper cut-off. Thus even a very weak residual transmittance of infrared light in the red waveband can produce up to a 10% error in the measurement of red radiance (Begni, 1982). The limit of the red band in both the SPOT HRV XS2 (0.615-0.68μm) and TM3 (0.63-0.69μm) reduces the risk of residual transmittance from the longer wavebands

Landsat MSS 6 (0.7-0.8μm) includes the noisy 0.70-0.74μm transition zone as well as the initial stages of enhanced reflectance from 0.75-1.1μm. The near-IR band of the SPOT HRV (0.79-0.89μm) and TM 4 (0.76-0.90μm) are better placed to record only near-IR radiance. The upper limits of the near-IR bands in SPOT and TM also reduce the influence of the minor water absorption band centred at 0.96μm. This is included in MSS 7, although the major absorption region from 1.3μm onwards is avoided.

In summary, the TM bands are the best match to the changes in absorption and reflectance which occur in the visible and near-IR wavelengths. This was also suggested by Tucker (1978) prior to the launch of the system. With the qualifications described in section 2.4.1 they are therefore expected to show the greatest sensitivity to change in features of the vegetation canopy. The SPOT HRV bands were designed to be compatible with the TM and a similar sensitivity is expected. The positioning of the MSS bands is clearly poor in comparison. However much of the detailed data on the spectral response of vegetation referenced in this and previous sections was prompted by and carried out after the launch of Landsat 1. The improvements in the specifications of the TM and SPOT HRV sensors have come from this information. Progress in detector technology has also allowed an acceptable signal to noise ratio to be maintained with a lower energy flux and therefore narrower wavebands.

2.4.3 Increased spectral information in the Landsat TM

The TM also records radiance in the blue, mid-IR and thermal IR wavelengths. If the information in these wavebands is independent to that in the existing visible and near-IR bands this spectral detail can be expected to improve the separability of vegetation targets in TM data.

Markham and Barker (1980), quoted in Badhwar and Henderson (1982), state that the new TM wavebands provide additional but not unique measures of canopy cover or status. Other studies (Williams et al., 1984; Acevedo, et al., 1984) find an improved classification accuracy in TM data which is due to the increased spectral information. The improvement is suggested to come from the mid-IR and thermal IR wavebands. TM data have been shown to have higher dimensionality than MSS data (Anuta et al., 1984; Townshend 1984; Malila et al., 1984; Crist and Cicone, 1984; Williams et al., 1984) and this is equated with an increase in information. However such studies do not differentiate between the effects of adding new wavebands and redefining the existing ones. The latter will also affect the form of the covariance matrix and therefore the number and definition of independent dimensions found in the data.

A number of studies with simulation data have shown that the mid-IR and thermal-IR can be correlated with each other and with other bands (Townshend, 1984; Lynn, 1984). The mid-IR has been found to be important for discriminating vegetation canopies and its omission on SPOT 1 and SPOT 2 HRVS is considered a serious if unavoidable limitation on the use of the imagery (Harris and Weaver, 1985; Townshend et al., 1983). A mid-IR band will be included on the HRV sensors of SPOT 3 and SPOT 4.

The blue wavelengths are dominated by pigment absorption and it is unlikely that they will add significant new information for vegetated canopies. In practice therefore the utility of the new information in the TM data will depend on the features of the target. It will be greatest where the diagnostic characteristics are the concentration of carotenoid pigments or marked changes in water relations which are not apparent or are masked by other factors in the visible and near-IR wavelengths.

2.4.4 Spectral matching between detectors and nominal vs. actual bandwidths

Slight differences in response between neighbouring detectors cause the 6 and 16 band striping which is visible in the Landsat MSS and TM data and the across track striping which can occur in SPOT HRV data. The MSS sensor acquires 6 lines of data from one ground scan as the mirror is swept across an array of detectors, 6 in each waveband. 16 lines of data are acquired simultaneously in a similar way in bands 1 to 5 and 7 of the Landsat TM. Four lines of data are acquired for TM 6. Two detectors are used for each of the 3,000 elements across track in each band of the SPOT HRV data, making a total of 6,000 detectors per band. These detectors are held in four staggered arrays which are recombined optically to produce a continuous line across track (Midan, 1986).

The differences in response between neighbouring detectors are due to residual differences in gain or offset, which cause radiometric striping, and slight differences in the spectral response which causes spectral striping. Radiometric striping is discussed more fully in section 2.5. Spectral striping cannot be corrected for by uniform radiometric calibration and so limits the ability to remove banding from images (Markham and Barker, 1983). Residual striping is a potential source of error in the data as it reduces the confidence with which differences in image tone can be interpreted as spectral differences in the target.

The effects of residual spectral striping in the MSS on Landsats 1-3 are discussed only briefly in the literature although the spectral response curves for individual detectors are available in technical documents and engineering reports (Hughes Aircraft Company 1972; Potter, 1972). The examples in fig. 2.7 demonstrate the variation in spectral response, especially spectral flatness, between different detectors in the MSS of Landsat 2 (MSS 4) and Landsat 4 (MSS 2).

Slater (1979) calculates a 16% difference in normalised output between the first two detectors in Band 5, Landsat 2 for a target of orange leaves. He concludes that to minimise residual striping, variation in channel to channel response for "important spectral signatures" should be kept to 1%.

Information on the spectral response of the Landsat 4 and 5 MSS sensors is more readily available in the literature (Markham and Barker, 1983, 1985). The response of individual channels in each of the MSS wavebands was found to be sufficiently similar to minimise residual striping (Markham and Barker, 1983). The first channel of band 2 (red), shown in figure 2.7, is an exception. In simulated output for a soya bean target this discrepancy results in a potential maximum within band striping of 6.2% in the red band. The channel to channel matching for the MSS systems on Landsats 4 and 5 was found to be generally better than that for those on Landsats 1-3, with the exception of the upper band limit of MSS 1 on Landsats 4 and 5.

The variations in average band limits and peak responsivity which exist across the series of MSS sensors imply that imagery from successive MSS systems will show different patterns of spectral striping. There will also be slight differences in absolute response between the same bands of

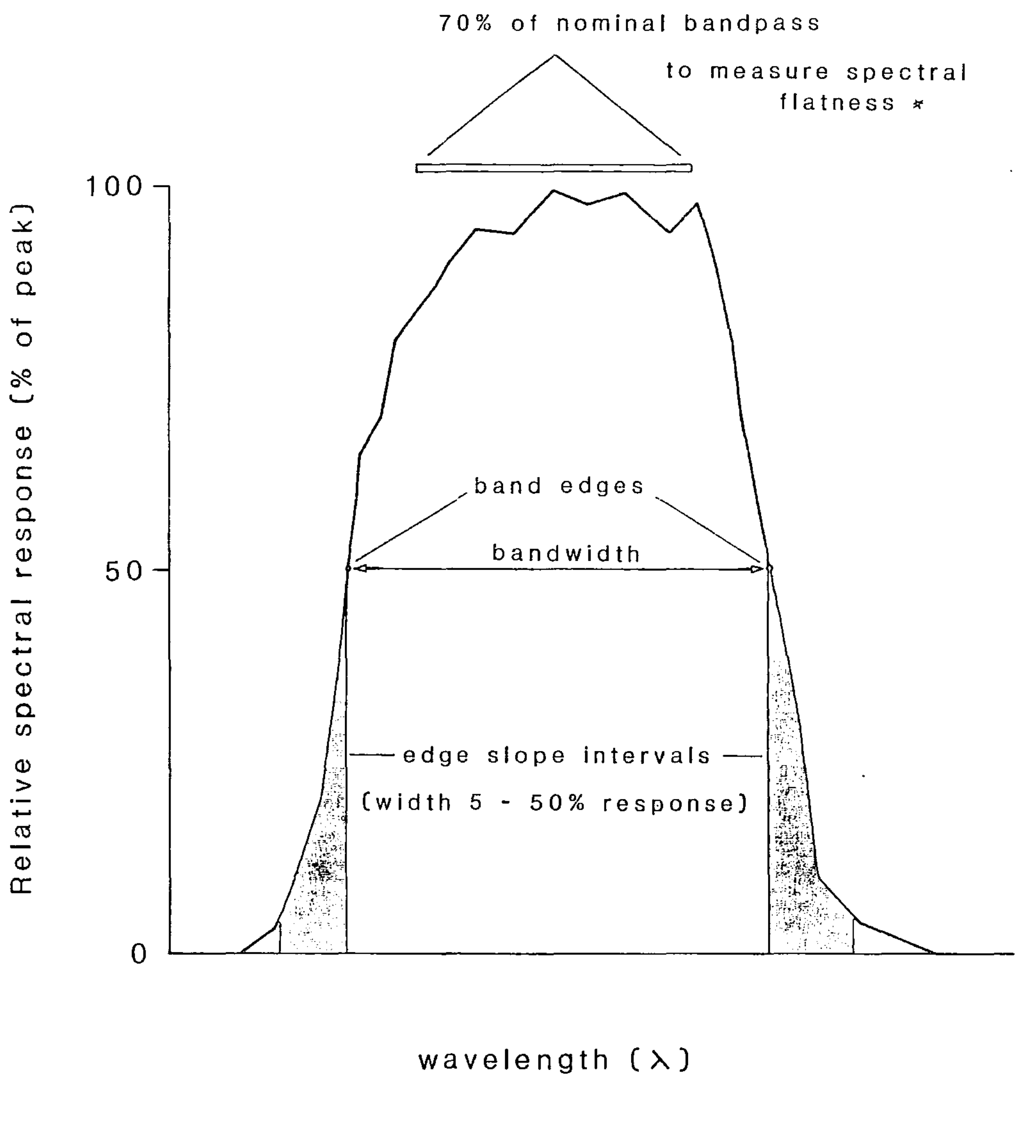


Figure 2.7a Parameters defining the spectral response of a detector. After Markham and Barker, (1983).

* positive (negative) spectral flatness = maximum positive (negative) percent deviation from mean response in the central 70

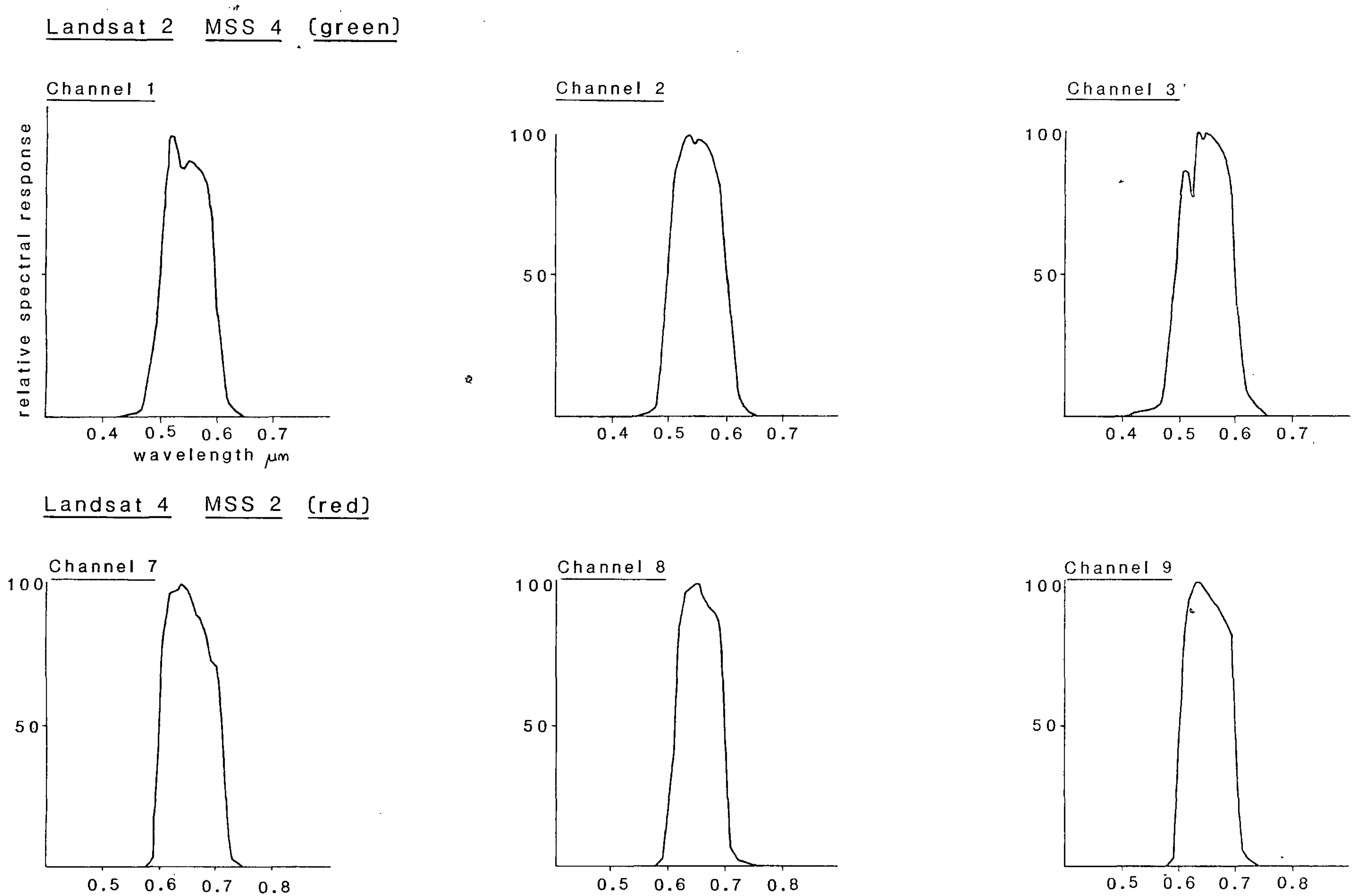


Figure 2.7b Channel to channel variations in spectral response: examples from Landsat 2 and Landsat 4. Note differences in spectral flatness, particularly for Landsat 2. Data from Hughes Aircraft Company (1972) and Markham and Barker (1985).

different systems. This will limit the accuracy with which real change in the target can be distinguished from artefacts of the sensor in multi-temporal data sets.

The spectral striping in the MSS data arises mainly from slight differences in the response of the individual filters over each detector. The relative spectral response of most channels on all the MSS systems failed to meet the filter specifications (Markham and Barker, 1983). In the TM a single filter covers all 16 detectors in one band and Markham and Barker (1985) state that this improves the uniformity of response between bands. The design specification, intended to reduce spectral striping from the level found in the MSS, was that the maximum difference in output between channels should be less than 0.5% of the minimum saturation level when viewing a specified radiance source.

Engel and Weinstein (1983) state that the spectral coverage of all detectors in the proto-flight TM meet the design specifications (table 2.5), with the exception of the upper bound on Band 6 in the thermal IR. The considerable differences in response between the thermal detectors are not considered critical, as the specified radiometric resolution has been met. Markham and Barker (1985) agree on the waveband limits, but note that the upper bandpass of TM5 is outside the design specifications of 1750 +/- 20nm, and therefore extends into an area of high attenuation by atmospheric moisture. There will therefore be a component of the received radiance in this band that is undesirably dependent on the amount of water in the atmosphere at the time of imaging.

Palmer (1984) derives slightly different figures for the TM bandwidth and central (effective) wavelengths of each detector, (and see Palmer and Tomisako, 1980), and these are recognised by Markham and Barker (1985) as being a more accurate indicator of response than the half-power width figures they use. Palmer's specifications, defined in table 2.6, take some account of the shape of the relative spectral response (RSR) curve, although the statistics are strictly comparable only when the curve follows

	Required		Observed	
	Lower band edge µm	Upper band edge µm	Lower band edge µm	Upper band edge µm
TM1	0.45	0.52	0.45	0.52
TM2	0.52	0.60	0.53	0.61
TM3	0.63	0.69	0.62	0.69
TM4	0.76	0.90	0.78	0.91
TM5	1.55	1.75	1.57	1.78
TM7	2.08	2.35	2.10	2.35
TM6	10.40	12.50	10.40	11.60

Table 2.5a Required and observed half-power spectral limits for the Thematic Mapper, from Engel and Weinstein (1983).

	Landsat 4		Landsat 5	
	Lower band edge µm	Upper band edge µm	Lower band edge µm	Upper band edge µm
TM6-1	10.42	11.60	10.45	12.41
TM6-2	10.42	11.64	10.45	12.43
TM6-3	10.42	11.66	10.45	12.41
TM6-4	10.42	11.74	10.45	12.43

Table 2.5b Half-power spectral limits for the thermal detectors 6-1 to 6-4 on Landsat-4 and Landsat-5 TM, from Markham and Barker (1985).

EFFECTIVE WAVELENGTH (centroid)

$$\lambda_c = \frac{\int \lambda . R(\lambda) d\lambda}{\int R(\lambda) d\lambda}$$

VARIANCE

$$\sigma^2 = \left\{ \frac{\int \lambda^2 . R(\lambda) d\lambda}{\int R(\lambda) d\lambda} \right\} - \lambda_c^2$$

where $R(\lambda)$ = spectral responsivity at wavelength λ

upper wavelength limit:

$$\lambda_c + \sqrt{3} . \sigma$$

lower wavelength limit:

$$\lambda_c - \sqrt{3}\, \sigma$$

bandwidth

$$2 \sqrt{3} . \sigma$$

Table 2.6a Effective wavelength, band limits and bandwidths as defined by Palmer (1984)

	Palmer		Markham and Barker	
	Effective wavelength	Band-width	Effective wavelength	Band-width
MSS1	552.8	116.0	551.8	110.0
MSS2	649.8	98.4	649.8	93.8
MSS3	756.7	115.9	759.0	110.0
MSS4	931.3	275.9	922.4	226.8
TM1	486.1	71.5	484.9	66.1
TM2	571.2	88.7	569.1	80.6
TM3	659.8	77.1	658.7	68.7
TM4	839.3	134.9	840.7	129.1
TM5	1678.0	227.0	1676.0	216.9
TM7	2217.0	269.0	2272.0	250.2

Table 2.6b Effective wavelength (λ_c) and bandwidth ($\Delta\lambda$) for the Landsat 4 sensors; comparison of figures from Palmer (1984) and 50% bandwidth definition from Markham and Barker (1983, 1985)

a normal distribution.

Whichever definition is used, it is clear that the channel to channel matching of the TM is an improvement on that of the MSS despite the larger number of detectors used. Uniformity of spectral response is regarded as a "most critical area" in the design of the SPOT HRV (Midan, 1986), with a design criterion for residual spectral variation over the whole array as a maximum of 5%. This is high in comparison with the TM criteria, but a realistic estimate given the large number of detectors in each band. It is likely therefore that there will be a small amount of residual spectral striping in the SPOT HRV data.

In summary, this section shows that the response of vegetated targets in the Landsat TM or the SPOT HRV wavebands is more likely to be directly related to identifiable features of the canopy than that in the Landsat MSS wavebands. The individual detectors of each waveband also have a more similar response in the TM. A change in radiance between successive lines in these data can therefore be interpreted most confidently as a real change in canopy features at the ground. The anticipated level of spectral similarity between detectors in the SPOT HRV sensors is below that required by Slater (1979), and may be difficult to meet because of the numbers of detectors. At least some residual striping is therefore expected in the SPOT HRV data. The extra spectral information in the Landsat TM data may contain independent discriminatory information for targets which are confused in the existing visible and near-IR bands.

The following section discusses the sources of noise in the sensors and the sensing process and the way in which they affect the quality of the data from each sensor system.

2.5 Sources of error in the sensing process.

Error is introduced to remote sensing data by the sensing process and by features of the sensor itself. The sources of noise and error are shown

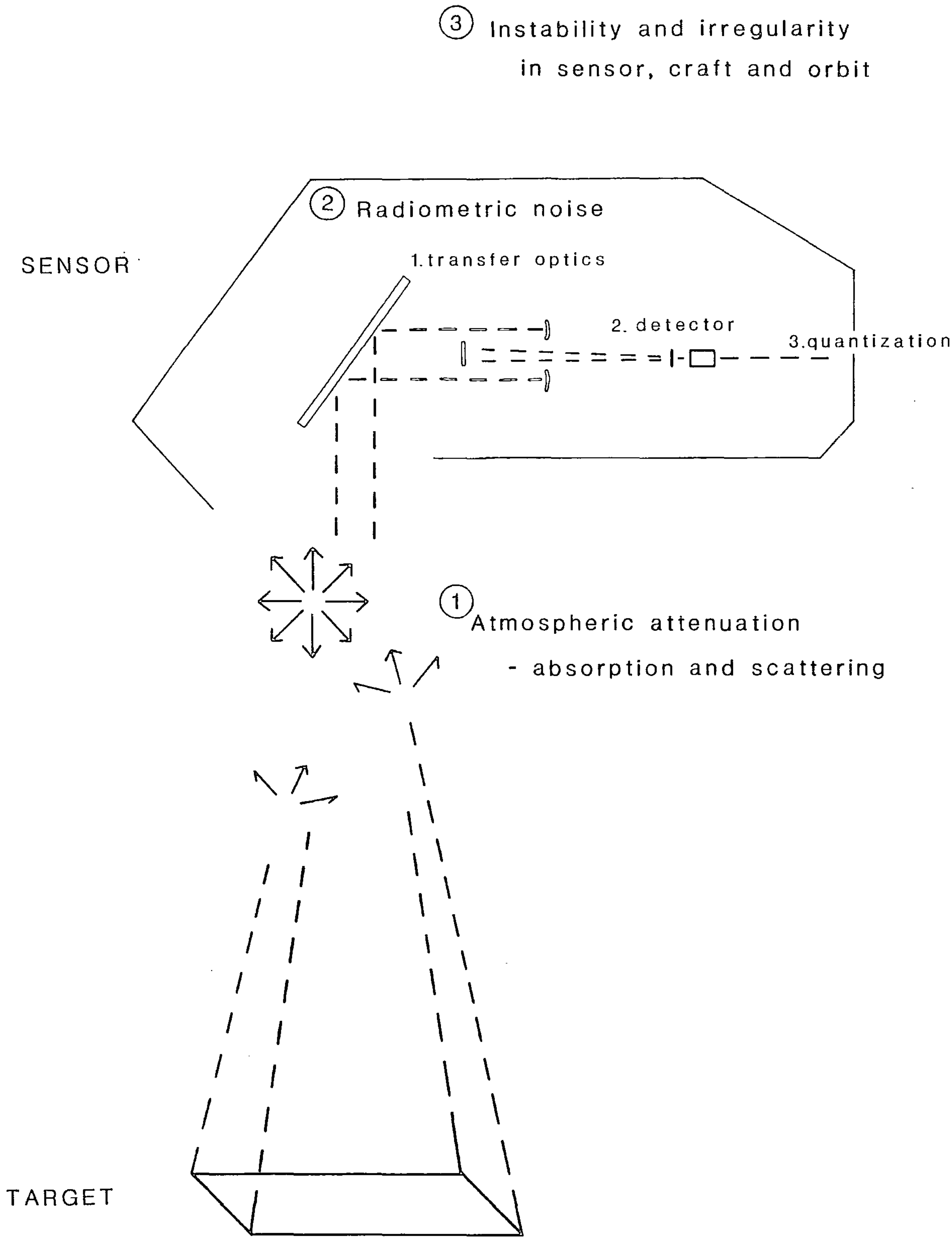


Figure 2.8 Error sources in the sensing process

schematically in figure 2.8. They can be divided into those that enter the signal before its reception at the sensor aperture, namely variation in irradiance (see Curran and Hay, 1986) and atmospheric distortion, and those which occur as the radiance is recorded by the sensor. The latter include inherent detector noise, the effects of quantization and the effects of spatial and temporal irregularities in the operation of the scanner.

This section examines, as far as possible, the importance of each noise source for the Landsat and the SPOT systems.

2.5.1 Atmospheric distortion.

The atmosphere alters both incoming and reflected or emitted radiation by absorption and scattering. The effect of such alteration is to lose information on the response of the ground target and to introduce radiance from other unrelated sources. Its effect on data is to reduce the contrast within a scene by adding a wavelength dependent flux. This means that subtle spectral differences at the ground may not be recorded by the sensor and also that grey tone patterns which do exist in the data may be related to patterns of moisture and scattering particles in the atmosphere as well as to ground features.

The mechanism of atmospheric distortion is described in figure 2.9. Incident radiance from the sun enters the atmosphere and is partially scattered or absorbed on its downward path (for example at point Z in figure 2.9). The point G on the ground surface therefore receives direct radiance from the sun and an element of the scattered flux from the surrounding hemisphere. Part of this combined radiation incident on G is reflected back through the atmosphere in the direction of the sensor. The reflected flux is again scattered and absorbed so that some spectral information from the ground target is lost. Spurious information is added from the scattering of incoming radiance which has not reached the ground (as at point D), and elements of the flux reflected from G2 and subsequently scattered at E. These additions collectively form the

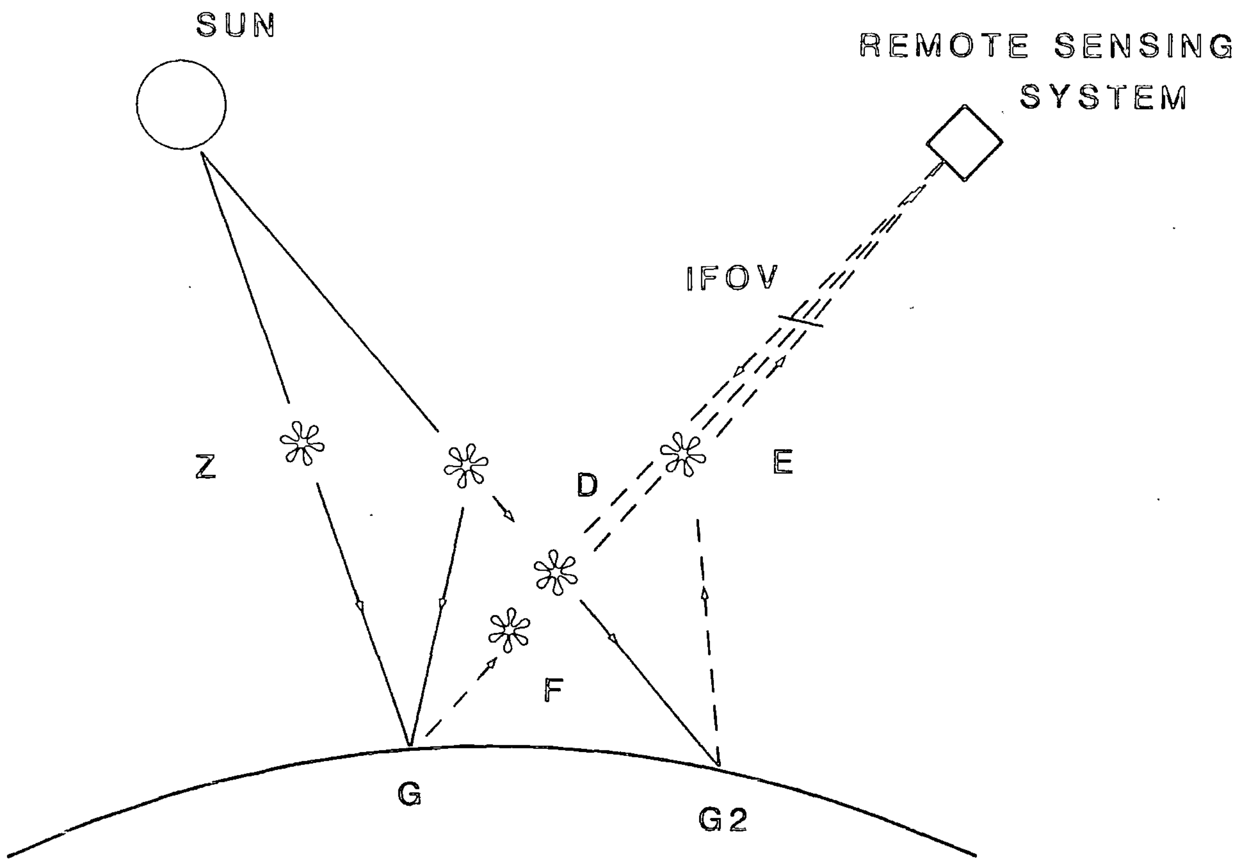


Figure 2.9 The role of the atmosphere in attenuating and scattering incident and reflected radiant flux. After Slater (1980).

atmospheric path radiance. They appear to the sensor to have come from the ground target but in fact contain no spectral or spatial modulation from the scene (Slater, 1980).

The main causes of atmospheric distortion are absorption and scattering. Absorption is a thermodynamically irreversible transformation of radiant energy into heat (Slater, 1980). Absorption by ozone forms a lower cutoff to atmospheric transmission at about 0.29µm. It recurs to a lesser extent in the visible wavelengths, with a local peak of absorption at 0.49µm, and a slight lowering of transmission throughout the red wavelengths (Begni, 1982). Generally however, atmospheric absorption from all sources is minimal in the visible and near-IR up to about 0.8µm, from which point the strong water absorption bands identified in section 2.4.1 are dominant. Atmospheric absorption is therefore expected to exert a strong influence on the two mid-IR bands of the TM, but have a negligible effect on all other wavebands of the Landsat and SPOT HRV sensors.

Atmospheric transmission in the visible and near-IR wavelengths is effectively controlled by the scattering of light by molecules and particulate matter. The effect of all forms of scattering is to dissipate radiance from a target, and increase the proportion of the received radiance that is unrelated to the ground target. All particles in the atmosphere scatter electromagnetic energy. The amount and type of scattering depends on the size of the particles, their composition and concentration and is wavelength dependent. Molecular scattering, described by the Rayleigh scattering coefficient, puts a lower limit of about 0.45µm on useful remote sensing of ground targets. TM1 (0.45 - 0.52 µm) is therefore affected consistently by scattering from molecules and small particles and the response in the SPOT HRV green band (0.50-0.59µm) is likely to include elements which will be affected by molecular scattering. None of the remaining bands of the Landsat TM, MSS or SPOT HRV sensors has a particular advantage or disadvantage in this respect.

The interaction of light with successively larger particles is described by Mie scattering and non-selective scattering (Slater, 1980). Mie scattering is most common in conditions of heavy atmospheric haze, and results in a general reduction in contrast in the imagery across the optical spectrum (Swain and Davis, 1978; Steven and Rollin, 1986). Non-selective scattering is dominant only when the atmosphere is heavily dust laden. Its effects are highly variable and depend on the movement of winds near the surface.

Detailed information on the size, type and density distribution of scattering particles at the time of sensing is not normally available. A relatively good approximation can be made by atmospheric modelling, for which a wide literature is available (Otterman and Robinove, 1981; Dave, 1981; Munday, 1983; with more recent contributions from Kaufman, 1985 and Richter, 1985). A residual uncertainty will remain from inadequacies in the model, the variation of the atmosphere over the time and space of imaging, and unknown elements such as the effect of terrain or sub-pixel cloud (Piwinski et al., 1983).

The amount of atmospheric attenuation varies systematically with the atmospheric path length, and therefore with the solar zenith angle and with the position of the target within the sensor's angular field of view. Kowalik and Marsh (1982), found a straight line relationship between grey tone and the cosine of solar zenith angle for Landsat imagery, although Potter and Shelton (1974) reached no firm conclusions on its effects. The magnitude of this effect is also related to the anisotropy of the reflectance from the canopy and will therefore vary for different targets (Royer et al., 1985). Barnsley (1986) reviews previous work and attempts a global model of off-nadir effects for a number of canopies.

Slater and Jackson (1982), and Dave (1981) found the variation across the small view angle of Landsat MSS to be of secondary importance to solar zenith angle and atmospheric moisture content. This implies that data used in multi-temporal analysis should be corrected for the effects of varying solar zenith angle before a quantitative comparison is made.

Slater (1980) suggests the use of sensors with a small (<20 deg.) angular field of view to minimise the scan angle effects. Both MSS and TM meet this requirement. The scan angle effect is however expected to be considerable for the SPOT sensor, when viewing at its maximum elevation of 27 deg. from nadir. This is discussed in detail by Slater and Jackson (1982).

2.5.2 Sensor noise

Error is introduced to the signal by the sensor in two ways. The signal undergoes radiometric degradation by the introduction of noise at the detector itself and the loss of part of the signal during quantization. A slight loss may also occur during the passage of the received radiance through the transfer optics of the sensor.

The second type of error involves the whole sensor-system and is shown by inaccuracies in the spatial representation of targets. These arise from instability in the scanner, the platform and the orbit.

2.5.2.1 Radiometric noise.

A small amount of noise can be introduced during the passage of incident radiation through the lens system to the detectors. The initial focal plane of the MSS consists of 24 optical fibres (6 for each of the 4 bands) separated by cladding. Each fibre transmits energy via an individual lens/prism system to a filter and detector and a very small amount of energy is dissipated in this process. The need for transfer optics was avoided in the TM where each of the visible and near-IR bands uses a 16 element monolithic detector mounted directly on the primary focal plane.

The mid- and thermal IR detectors of the TM are located on a secondary cooled focal plane and relay optics are used so that the two focal planes appear as one optically. Here the relay mirrors are coated with aluminium, which has excellent reflectance properties in the 1.5-12.5μm region of TM bands 5,6 and 7 (Engel and Weinstein, 1983). The degradation due to transfer within the sensor optics is minimal compared to the effects of detector noise.

As introduced in section 1.2 a detector irradiated with a constant flux maintains a certain unpredictable fluctuation in output which is known as noise. The Landsat and the SPOT HRV sensors have different types of detector and are affected by different types of noise. A detailed discussion of the types of detector noise, and their relative importance for each system are given by Norwood and Lansing (1983), and Slater (1980) and summarised in table 2.7.

The noise equivalent reflectance difference (NEΔR), or noise equivalent temperature difference (NEΔT) (section 2.3) specifies the input power difference which is equivalent to the noise output from the system or the component. It is therefore an indication of the changes in output that can be reliably attributed to change in the incoming radiance. In practice this approximates the NEΔR/NEΔT of the detector. Table 2.1 lists these figures as quoted for each band of each system, and, for the SPOT HRV, its change with pointing direction. Further definitions of the NEΔR/NEΔT and the measures derived from it are discussed in Slater (1980) and Norwood and Lansing (1983).

A stated objective in the design of the TM was to improve the noise levels from those of the Landsat MSS (Salomonson et al., 1980) and a similar criterion is noted for the SPOT HRV system (Chevrel et al., 1981; Midan, 1986). The predicted low noise level for the SPOT HRV is largely a result of the increased dwell time allowed by the pushbroom method of scanning and early results suggest that the design criteria have been met (Baudouin, 1986; King, 1987). The mid-IR bands of the Thematic Mapper have the poorest NE R figures. This is expected as there is a relatively low energy flux at these wavelengths, and the adjacent areas of low atmospheric transmittance impose constraints on the bandwidths. The noise fraction is therefore a relatively high percentage of the absolute flux.

The sensors examined here have multiple detectors. To maintain a

JOHNSON, NYQUIST or THERMAL noise. Caused by random motion of charge carriers in a resistive element, gives rise to a random electrical voltage across the element. Affects all detectors but photomultipliers are affected to only a small degree.

MODULATION or CURRENT noise. Depends on surface state of detector and contacts. Affects all detectors.

GENERATION-RECOMBINATION noise. Caused by statistical fluctuations in the rates of generation and recombination of charged particles in the sensitive element of all photodetectors.

SHOT noise. Caused by discontinuity in flow of current due to the discrete nature of electrons in a current.

QUANTUM and BACKGROUND noise. Generation-recombination and shot noise due extraneous radiance arriving with signal.

Table 2.7a Outline of types of detector noise. See Slater (1980) and Norwood and Lansing (1983) for details.

1. THERMAL : detector is heated as it absorbs flux. Heating changes physical property of detector and therefore output. Needs time to reach thermal equilibrium, not practical for most remote sensing applications.

2. QUANTUM or PHOTON : An absorbed photon of the signal energy will activate an electron, affecting the electrical characteristics and therefore output of the detector.

Types:
- photo-emissive: eg photomultiplier tube of Landsat MSS. Max. wavelength c 1.0 um
- photoconductor: used for TM5 and TM7. Materials (see table 2.2) need less cooling in operation.
- photodiode: similar operation to photoconductor. No cooling required if made of silicon (MSS7, TM1-4)
- charge-coupled devices (CCDs) as SPOT HRV

Table 2.7b Types of detector, from Slater (1980) and Norwood and Lansing (1983).

consistent signal between detectors calibration occurs over space (between all detectors of the same band) and time (between successive signals from the same detector). When multiple detectors are used to acquire adjacent image lines simultaneously, regular striping may appear in the imagery. As discussed in section 2.4.4 this is caused by incomplete compensation for radiometric differences between detectors and slight differences in their spectral sensitivity.

Table 2.1 lists the design specifications for the radiometric matching of detectors in each sensor and Midan (1986) specifies in addition that the overall relative calibration is expected to be 1% for the SPOT HRV. Early results from test scenes of the SPOT HRV data suggest that these criteria have been exceeded in all cases except the panchromatic mode of HRV 2 where residual striping persists (Baudouin, 1986).

The NASA Landsat Image Data Quality Assessment (LIDQA) programme has been instrumental in making the results of a thorough investigation of the channel to channel calibration of the TM available to the user community (see special issues of Photogrammetric Engineering and Remote Sensing 51(9) 1985 and IEEE Transactions on Geoscience and Remote Sensing GE-22(3), 1984). Fischel (1984) found three types of radiometric striping in early TM data. These were detector to detector, scan to scan (forward to reverse) and banding made up of a number of scans. Murphy et al. (1984) found variations in response of 1 to 4 DN for different lines of the same detector and Fusco et al. (1986) confirm Fischel's observations on scan to scan banding. All three papers suggest alternative algorithms for correcting detector to detector response after the original appeared inadequate. Poros and Peterson (1985) also describe methods for destriping TM images and Singh (1985) outlines the corrections developed to resolve problems of radiometric matching discovered after launch. Bernstein et al. (1984) found generally good detector to detector calibration, with a residual uncertainty due to rounding errors in digitisation. He does not apparently consider the option that this might be spectral striping.

Generally, removal of radiometric errors is of a high standard in TM data and represents an improvement over the MSS, despite the larger number of detectors. This improvement was an objective in the TM design specification.

In practical terms it means that the fine detail in the grey tone patterns of data from the TM and the SPOT HRV can be interpreted as real change at the sensor aperture, to the levels specified in table 2.2. The level of confidence with which this detail can be interpreted is lower for the MSS data.

Inaccuracies in calibration over time are less immediately obvious in the imagery but they are important for multi-temporal analysis. As both axes of an image are measured in time as well as space they may also be important within a scene.

The process of calibration over time includes the initial absolute calibration and periodic inflight relative calibration. Slater (1980) notes that there are fundamental inadequacies in the laboratory standards used for absolute calibration, and in secondary reference sources suitable for withstanding launch and long term flight conditions. The problems of transfer from a primary to a secondary standard are discussed further by Norwood and Lansing (1983). Slater (1983) and Price, (1987) discuss the problems of absolute and relative calibration in general and the limitations of the inflight calibration of the TM and the HRV sensors in particular.

Relative calibration onboard the Landsat is supplied by exposure to a calibration lamp on the retrace scan for the MSS and during the turnaround between scans for the TM (USGS, 1982). Because of the large number of detectors involved the CCD arrays of the SPOT HRV are calibrated only once a week, by exposure to a tungsten lamp.

As the Landsat spacecraft passes over the polar regions, solar flux is reflected onto the fibre ends of the MSS from one of four small mirrors in front of the scan mirror. This provides an absolute check on the stability of the onboard calibration lamp which is considered acceptable by Slater

(1980). A similar method operates for TM (USGS, 1982). Field tests by the Hughes Aircraft Company showed that the mean responses of the 4 MSS bands on Landsat 1, measured over a large calibration target, agreed to within 1.5%, 6%, 5% and 4.5% of those calculated from laboratory measurements (Slater, 1980).

Absolute in flight calibration of the SPOT HRV sensors occurs when bundles of fibres are exposed to solar irradiation, which is collected outside the HRV unit from three different sun-satellite attitudes, and transmitted to the focal point of the calibration unit by optical fibres (Midan, 1986).

Complete removal of radiometric striping in an image is limited by the sensitivity of the analogue to digital conversion which occurs before the transmission of the signal to the ground. The rounding errors involved in the digitisation process are a source of error in that potential discriminatory information is lost. It also means that residual radiometric striping is inseparable from spectral striping. Grebowsky (1975) examines the compounding effect of digitisation on detectors which have slightly different responses, specifically those of the Landsat MSS. The radiometric resolution of each system is given in table 2.2.

Radiometric resolution per se has received scant attention in the literature. One of the few general treatments is by Tucker (1980b), who modelled the output of a noiseless sensor from ground radiometer data. He found that 128 quantization levels gave results approximately 1% better than 64 levels for the regression of radiance against canopy variables. A 1-3% improvement was found for 256 vs 64 levels, and it was concluded that 128 or 256 quantization levels appear optimal for satellite monitoring of terrestrial vegetation, although the work was not extended to complete canopies. This modest improvement must be set against the increased data rates and data processing time and the implications for the spatial and spectral parameters of the system.

A number of comparative studies have attempted to quantify the extra discriminatory information in the TM which is caused by its increased radiometric resolution compared to the MSS (Williams et al., 1984; Bernstein et al., 1984; Price, 1984; Buis et al., 1983; Malila et al., 1984). Williams et al. and Buis et al. conclude that the higher quantizaton gives more information, where this is measured by classification accuracy. Both Bernstein et al. and Price use entropy as a measure of information. Bernstein et al. suggest that the two extra bits in the TM extend the range of the data in both directions, as well as increasing the quantization detail within the previous range of the MSS.

The noise introduced to the signal by the radiometric characteristics of the sensor are minimised at the design stage of each system. They are in fact miniscule when set in the context of the operating environment. In general however the Landsat TM represents an advance on the MSS in all parameters of response and fidelity. Similar stringent quality requirements are set out for the SPOT HRV sensors and the care which is taken to meet them is particularly emphasised by Midan (1986).

The radiometric errors which are most apparent to the user will be the effects of residual differences in output between detectors over both time and space. Despite the design specifications this is expected to be highest and most variable for the SPOT sensors. An absence of visible striping does not necessarily imply an absence of error, particularly where the effects of radiometric and spectral striping may work against each other. Similar criteria apply to the effects of quantization. It is therefore important to have at least an elementary understanding of the degree to which these factors affect the spectral response of a target as recorded by the different sensors.

2.5.2.2 Spatial representation of targets

The second set of errors introduced by the sensor concern the spatial representation of targets. They include the effects of instability in the sensor, craft and orbit and the accuracy with which images from different wavebands are registered. The effect of the spectral characteristics of the target (discussed in section 2.3.2) is a separate issue and is not reiterated here.

The spatial resolution for the Landsat MSS and the SPOT HRV systems given in table 2.2 is the IFOV subtended by the detector, or its angular equivalent, which is strictly controlled by the geometric properties of the imaging system. The 30m x 30m spatial resolution noted for the TM is based on the system's point spread function (section 2.3). Errors will also arise from the fact that all targets within the IFOV do not contribute equally to the recorded signa The magnitude of this effect is target dependent (see Forshaw et al., 1983 for discussion). This section concentrates on features of the sensor as set out in Figure 2.10.

Figure 2.10 outlines the features of the sensor, craft and orbit that can affect the projection of the IFOV to the ground. The footprint will vary slightly and systematically across track as the mirror moves through its scan angle. Instability in the pointing accuracy, height or speed of the platform, an irregularity in the speed of the scanning mirror or the spacing in time between successive samples of the detector output will have a direct effect on the size and location of the area viewed. The majority of these effects can be measured closely and removed during processing.

All three systems carry instruments to monitor pointing and positioning accuracy throughout the orbit and these are described in table 2.2. Typically they consist of a measurement/control system, and a second independent instrument that measures the residual error which is not corrected in flight. The information from this instrument is used in the fine processing of the sensor data at the ground station. Clearly the TM attitude and measurement control system is a great improvement on that of the MSS (table 2.2). This is attributed to the modular design of the spacecraft (Salomonson et al., 1980). The SPOT platform has a similar design and similar accuracy in attitude control. High structural stability, to minimise effects which would cause image distortion/modular axis deviation, has been an important consideration in the design of the SPOT system (Midan, 1986). When operational, a network of global positioning systems will allow precise orbital location, to about 10m, for the TM (Salomonson et al., 1980).

The alignment of successive pixels or lines along the satellite track

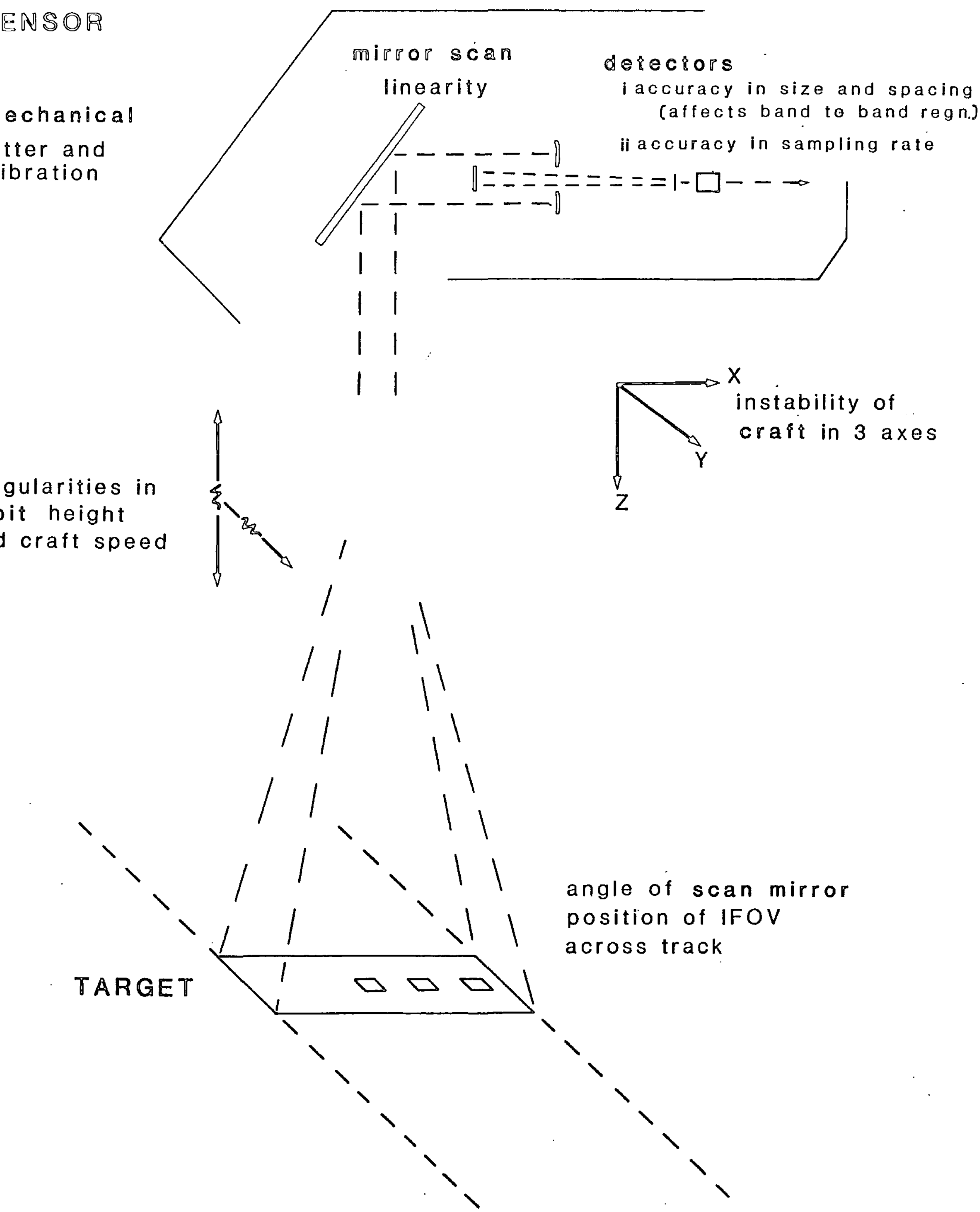


Figure 2.10 Features of the sensor and the spacecraft that can cause error in the spatial repesentation of objects.

depends on the matching of the scan speed and the spacecraft speed. In the MSS the forward motion of the spacecraft is sufficient to ensure linearity between one active scan and the next. The improved resolution of the TM has enforced a longer dwell time for each element, and data are acquired on both forward and backward scans. Two scan line mirrors effectively move the IFOV of the detectors, so that each scan is perpendicular to the spacecraft track.

If the mirror scan is not linear, i.e. the rate of change of angle over time is not constant, or if the rate of sampling across the scan is not constant, successive picture elements will represent ground cells of different sizes. Linearity is particularly important in the registration of different wavebands (see below), for pixels recorded by different detectors in the same waveband and for systems with finer spatial resolution. (Gordon, 1983; Fischel, 1984). The problems of a continuous scanning mirror are avoided in the SPOT HRV sensors.

In both TM and MSS the scan mirror oscillates in a 'bang-bang' manner (Blanchard and Weinstein, 1980; figure 2.1). To maintain a constant speed, torque is applied at the turnaround for the TM, and throughout the backscan for the MSS (Lansing and Cline, 1975). The scan position monitor on the MSS measures the angular position of the scan mirror to an accuracy of 10urad (Lansing and Cline, 1975) and a similar instrument is carried on the TM (USGS, 1982).

Fischel (1984) states that, if uncorrected, spacecraft vibrations and differences in mirror scan velocity between the forward and backward sweeps can cause mispositioning in TM data of up to 8 IFOVs along scan and under or overlap of successive scan lines. The effects of spatial misregistration are most apparent in data with a fine spatial resolution. The improved accuracy in measuring and correcting these errors is therefore important for the TM data.

The concept of accuracy in spatial representation also includes the accuracy of spatial registration between wavebands, that is whether the ground area represented by a single pixel in a multi-spectral image is the same for each band. The accuracy of band to band registration has implications for all routine multispectral image processing tasks and particularly for classifications. The accuracy specifications for band to band registration are given for each system in table 2.3. Swain et al., (1982), working with MSS data, suggest that a misregistration of as little as 0.3 pixel can have severe effects on interpretation.

The accuracy attainable in band to band registration is a straight forward function of accuracy in the layout of the detectors and in the system mechanics and electronics. The fine adjustment of pixel registration occurs at the processing stage and compensates for the sampling pattern of the scanner and the physical layout of the detectors. Clearly band to band registration will be easiest where there are fewer detectors, or where they are close together in a single plane and their spacing can be measured accurately.

In the MSS sensor, each of 24 detectors in the MSS is read sequentially in a total period of 9.958us. The area of ground represented by a single pixel is not therefore sampled at the same time in all bands. A detailed treatment of the relationship between scan time and band to band registration can be found in Gordon (1983), Freden and Gordon (1983), and USGS (1982).

In the TM, the 16 detectors of each band are arranged in two columns. The output of each column of detectors is held in turn, then read out sequentially. The total hold and read out time is 9.611 secs. This method effectively reduces the number of detectors considered to two, so that corrections can be applied uniformly to either set of odd or even detectors. A similar approach is taken in the SPOT HRV, where 6 "chains", 2 per band, are used to process the CCD arrays in the period taken to acquire a line of data (see Midan, 1986). Preliminary results from the SPOT HRV system state that the band to band registration in the multi-spectral mode is .2 pixel which is an improvement on the design level. Midan (1986) states that the centre of each detector is no more than 3μm from its nominal position and that the arrays of different bands are "very accurately positioned relative to one another so that the three images .. are perfectly registered" This accuracy is protected by the design of the detector box, which has a minimal sensitivity to temperature variations and thermal gradients.

In analysis of early TM data, Walker et al., (1984) and Wrigley et al., (1984) demonstrated the importance of the physical layout of the system optics. For bands within the same focal plane, the mean misregistrations were within the design limits of 0.2 pixels. In comparing bands between the cooled and uncooled focal planes, he found a consistent mean misregistration of 0.5 pixel along scan, against a design specification of 0.3 pixel, and 0.2 -0.3 pixel along scan. Wrigley et al. note however that most of this variation could be removed by processing software. This is confirmed by Bernstein et al. (1984), who found from visual assessment and cross correlation that bands 1 - 4 were registered to each other to within 0.1 pixel, and that bands 5 and 7 were registered to about 0.7 pixel with respect to band 1. Desachy et al., (1985) found similar results but also some occurrence of mis-registration between TM5 and TM7 of as much as 1.0-1.2 pixels, most probably due to a fault in the TM5 detectors.

2.6 Summary and Conclusions

This chapter has examined, for the SPOT HRV and the Landsat TM and MSS sensors, the accuracy of two assumptions basic to the interpretation of remotely sensed data; namely that at least some of the wavebands recorded are measuring features of the target that are meaningful to the interpreter, and that a density change in the image is a faithful record of change in spectral response at the ground.

The discussion of section 2.4 concludes that of the three sensors the spectral response of vegetated targets is most likely to be directly related to identifiable features of the canopy in the wavebands of the

Landsat TM or the SPOT HRV systems.

In addition, the accuracy and stability of the spectral and radiometric calibration between detectors and over time in the TM instrument means that, for comparable bands from the three systems, a change in image intensity in the TM data can be interpreted most accurately as an actual change in radiance at the ground. The confidence in this assertion will be reduced however in the blue and the mid-IR wavebands, which are affected by atmospheric distortion (section 2.5.1).

The importance of spectral resolution in delimiting moorland targets is discussed in detail in chapter 5. The possibilities of extending the spectral feature space by using multi-temporal data are examined in chapter 6.

According to the design criteria and early results from the SPOT HRV systems the spatial registration errors in the SPOT HRV and the Landsat TM data are approximately equal and an improvement on those of the Landsat MSS. It seems doubtful however whether these standards will be maintained in the SPOT HRV data because of the large number of detectors in each array.

In terms of spectral and radiometric characteristics the Landsat TM system therefore produces data in which vegetated canopies can be isolated and recognised more reliably than they can in data from the Landsat MSS or the SPOT HRV system. However, the practical use of the data also depends on the spatial periodicity of the vegetation in relation to the IFOV of the sensor. The effects of spatial resolution on the spectral discrimination of moorland targets is examined in detail in chapter 7.

Chapter Three: Land use conflicts in upland Britain and the North York Moors. The role of remote sensing in their solution.

3.1 Introduction

This chapter elaborates on the reasons for selecting heather moorland in general and the North York Moors in particular to test the use of remote sensing for managing natural and semi-natural communities. Section 3.2 outlines the relationship between remote sensing for agricultural and environmental purposes and introduces the main land use conflicts present in upland Britain.

Section 3.3 describes the moorland environment and current land use conflicts in more detail. Section 3.4 describes the physical environment and management problems of the North York Moors, used as a test area throughout this research, and how remotely sensed data might best be employed in their solution. Section 3.5 links this chapter to the discussions of chapters 1 and 2 by identifying the parallels between conventional vegetation analysis and the interpretation of remotely sensed data. These concepts are developed further in the analysis of ground radiometer data in chapter 4.

3.2 Remote sensing of natural vegetation

From early experiments with the the Michigan scanner (described in chapter 1) to the regular use of data from the the Landsat sensors, remote sensing of vegetation has concentrated on the measurement of agricultural targets, typically in large area crop surveys such as the LACIE project (NASA, 1978; Amis *et al.*, 1981).

The term agriculture however refers to " all practices of cultivating the soil and rearing animals " (Oxford English Dictionary). In the global agricultural economy there is a continuous gradation from the intensive cultivation of annual crops to the extensive use of natural and semi-natural communities for animal husbandry. The principal variables in this gradation are the intensity of management and the amount of alteration or replacement of the original vegetation.

Remote sensing for agricultural purposes centres on the estimation of crop yields, expressed as output per unit of crop or stock. It includes the elements of census taking, stress detection, and change monitoring, as well as the more general problems of entity detection and identification. If the same area is monitored for environmental reasons, the emphasis changes to the delineation and identification of communities.

The vegetation resources of upland Britain are used in an extensive agricultural system dominated by grazing and also have value for wildlife conservation and informal outdoor recreation. There is overlap between the monitoring requirements of different land uses and remote sensing has considerable potential as a source of information in each form of management. The distinction between the agricultural and the environmental approaches to data analysis is lessened in these areas as the delineation and identification of communities is a prerequisite to calculating parameters of agricultural productivity such as carrying capacity.

The spatial resolution of the Landsat MSS relative to the average field size in Europe (fig 3.1) has meant that satellite remote sensing has been largely ignored for conventional crop monitoring in the UK (Wooding, 1983 and pers. comm., 1985). Although the resolution of TM and SPOT HRV is better suited to inventory at this scale, there are a number of problems in the accuracy of multi-spectral classification that make the data impractical for day to day use (Hooper, pers comm. 1986). The greatest contribution of remote sensing for agricultural purposes in the UK is therefore likely to be in the inventory and management of upland areas. Information on rates of land use change in the uplands are not available from existing sources and are needed for agricultural policy, planning and advisory services (Tarran, 1985).

Recent experiments in the use of remote sensing data in the uplands include an evaluation of its potential for monitoring grazing pressure on

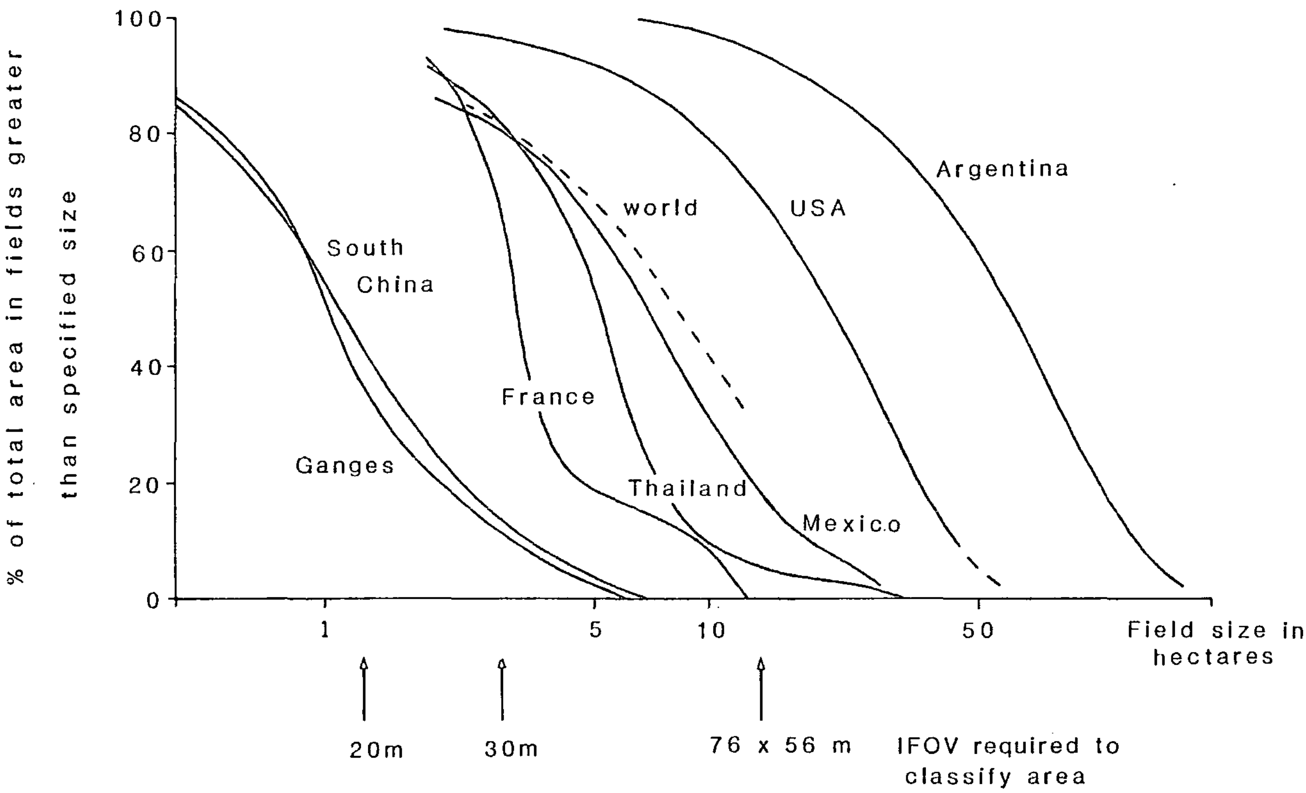


Figure 3.1 Relationship between field size distribution and spatial resolution requirements (IFOV) of remote sensing systems. After Townshend and Justice (1980)

upland pasture (Oxley and Williams, 1985), and for mapping the distribution of different types of grass sward (Tarran, 1985; Hume et al, 1986). Only the work by Tarran deals specifically with the agricultural implications of the results. The others are more concerned with the effects of agricultural practice on the conservation of particular habitats. Curtis (1984) reports on the experimental use of Landsat MSS data in the inventory and monitoring of the Exmoor National Park. The Nature Conservancy Council (NCC) are interested in the use of satellite sensor imagery to increase the efficiency in monitoring important sites and the use of remote sensing is an increasingly important part of the organisation's work (Budd, 1985).

Curran and Plummer (1985) showed however that relatively few researchers are using remote sensing data to address models and problems established within disciplines outside remote sensing, such as ecology or conservation. Most are concerned with the information content of the imagery per se. Such exploratory work is needed to allow the best use of remote sensing data, but continued experimentation should not hold back the application of remote sensing as a data gathering technique for natural and semi-natural communities. There is a recognised need for the plant communities of upland Britain to be mapped and monitored for both ecological and agricultural purposes and alternative sources of data are scarce. If the data are appropriate, remote sensing can be expected to make an immediate practical contribution to management over extensive areas. It is therefore important that the problems tackled even in experimental research are real ones and that the work involves the scientists and managers who will be using the data in the future.

Heather moorland in particular is a semi-natural habitat under considerable and continuing pressure from a range of conflicting land uses. Where the environment is favourable, the moors are used as rough grazing for sheep and for rearing game birds. They also have an important function in nature conservation and informal recreation.

Much of the moorland areas of England and Wales are within one of ten National Parks. The National Park Committees have a statutory duty to preserve and enhance natural beauty and to promote public enjoyment, subject to the needs of agriculture and forestry and to the economic and social interests of rural areas (Council for National Parks (CNP), 1985). An objective and sensitive ordering of management priorities is needed if these aims are to be translated into workable management strategies.

3.3 The moorland community

3.3.1 Vegetation

The open moorlands of upland Britain are typically dominated by dwarf shrub species, particularly heathers. They are a largely man-made landscape and their existence depends on a continuing programme of management which prevents succession to scrub and forest. Gimingham (1972) describes the variants of upland and lowland moorland and heathland in some detail and these are summarised in Table 3.1. Apart from some of the mountain heaths their unifying feature is the dominance by ericoid shrubs, particularly Calluna vulgaris. Erica cinerea and Erica tetralix are co-dominants where the substratum is particularly dry or wet respectively. Vaccinium myrtillus and V. vitis-ideae, grasses and sedges may occur locally.

The widespread dominance of Calluna vulgaris owes much to the physiological and morphological characteristics of the species. A number of intergrading stages in the growing cycle were first recognised by Watt (1955). His description is reproduced in Fig 3.2. The accompanying changes in productivity, microenvironment and associated species have been reported extensively in the ecological literature (see, for example, Barclay-Estrup, 1969, 1970, 1971; Coppins and Shimwell, 1977; Grace and Woolhouse, 1974; Miller and Miles, 1970; Miles, 1979).

The productivity of heather reaches a maximum in the 'building' phase 8 - 15 years after establishment. After this age the heather enters the mature

Mountain heaths	Dwarf mountain heaths Dwarf juniper heath Mountain vaccinium heath Rhododendron heath Sub-montane Calluna-Antennaria dioca heath
Dry heaths i. Oceanic	 Calluna-Empetrum hermaphroditum heath Calluna-Erica cinerea heath Calluna-Ulex galii heath Calluna-Ulex minor heath Erica vagans heath Calluna-Scilla verna heath
ii. Northern	Calluna-Vaccinium heath Calluna-Empetrum nigrum heath Calluna-Arctostaphylos uva-ursi heath Calluna sieglingia heath
iii. Southern	Calluna-Genista heath Erica scoparia heath
Humid and wet heaths	Humid heaths with Calluna and Erica tetralix Humid heaths with Calluna and Eric ciliaris Wet heaths with Calluna and Erica tetralix Calluna-Eriophorum vaginatum wet heath Upland Calluna-Eriophorum vaginatum wet heath

Table 3.1 Categories of heath community, from Gimingham (1972)

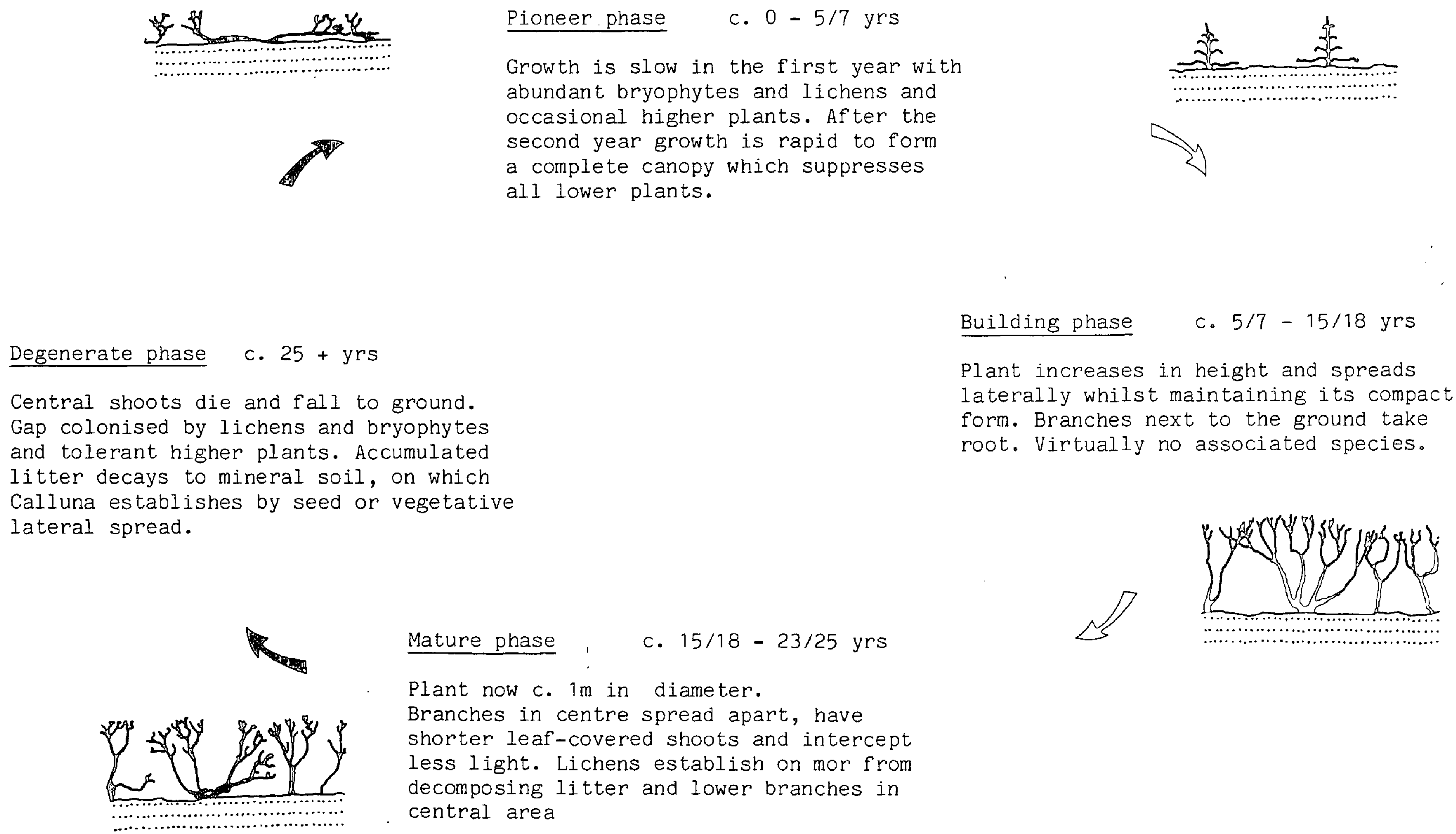


Figure 3.2 **Stages in the life cycle of heather (Calluna vulgaris). After Watt (1955) and Gimingham (1972).**

and degenerate phases and productivity declines. As the major economic use of the moorlands lies in raising game birds and sheep it is important to maintain a high productivity, that is a high proportion of green shoots, over as much of the moor as possible. Typical moorland management therefore consists of creating a vigorous monoculture of heather by burning the moor in small strips on an approximately 15 year rotation. The small strips ensure a variety of cover and food for stock and give rise to the typical patchwork appearance of managed moorland (figure 3.3). The Calluna regenerates quickly from seed and vegetatively to start the growth cycle again at the pioneer stage.

The re-establishment of Calluna as dominant typically proceeds through a secondary succession of lichens and mosses, grasses and other herbaceous species to the full heather canopy. The nature and rate of succession is determined by the rate of regrowth of the Calluna, which is in turn controlled by the age and environment of the heather stand at burning and the intensity of the fire (Whittaker and Gimingham 1962; Grant 1968). On a wet substrate, sedges such as Eriophorum may regenerate faster than Calluna and persist for a number of years or gain a permanent advantage. Mat grass species act in a similar way on dry soils. Miles (1979) notes that the stages of succession to the full heather canopy is more correctly a regeneration as they are merely temporary local disturbances between phases of heather dominance. The aim of moorland management is to minimise these seral stages and promote rapid development of the full heather cover.

3.3.2 Land Use conflicts.

As noted in section 3.2 a large proportion of each of the ten National Parks is open grass or heather moorland (table 3.2). The open landscapes typify the feelings of freedom and space for which the Parks were created. The Parks were designated under the 1949 National Parks and Access to the Countryside Act and each National Park Committee has a statutory duty to conserve the landscape and promote opportunities for informal outdoor

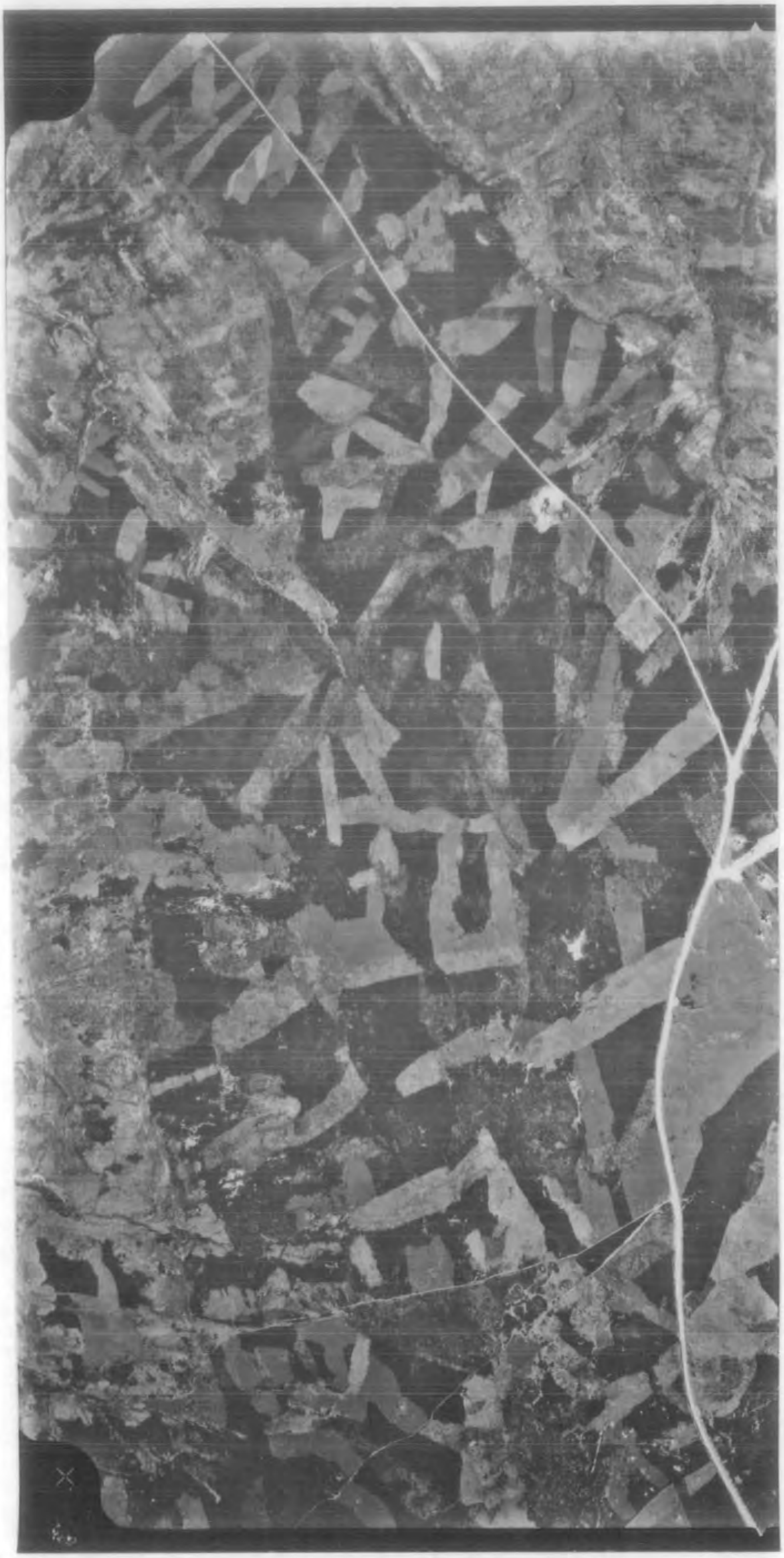


Figure 3.3 Vertical aerial photograph of heather moorland (North York Moors) managed by rotational burning. Dark areas are fully established canopies. The light and mid-grey patches are newly burnt or in the process of regenerating. Data from NERC, as part of the 1983 MSS airborne simulation.

National Park	farmland (encl.d) %	open moor %	forest %	decid. woods %	other %
Brecon Beacons	46.0	42.0	8.0	4.0	-
Dartmoor	35.0	52.0	9.0	*1	4.0
Exmoor	57.0	28.5	5.0	5.0	4.5
Lake District	33.0	50.0	6.0	5.0	6.0*2
Northumberland	9.5	71.0	19.0	0.5	-
North York Moors	42.0	35.0	18.0	5.0	-
Peak District	49.0	39.0	7.0	*1	5.0*3
Pembrokeshire Coast	84.0	12.0	3.0	1.0	-
Snowdonia	21.0	60.0	12.0	2.0	5.0
Yorkshire Dales	41.0	56.0	2.0	1.0	-

Table 3.2 Distribution of land use in the ten National Parks, data from CNP (1985).

1* Figure for forestry is total conifer and deciduous woodland
2* Includes 3% lakes
3* Industry/water supply

recreation. The land use conflicts decribed in this section are clearly not confined to National Parks but are made more explicit as well as exacerbated by the legislation which may support a number of alternative land uses for one site.

The conservation of wildlife and habitats is generally recognised as an integral part of conserving the landscape (North York Moors National Park (NYMNP), 1981a). The inter-relationship of natural beauty and nature conservation was a central theme of the Dower report (Dower, 1945), which, with the Hobhouse report of 1947 (Ministry of Town and Country Planning, 1947), formed the base for the 1949 Act. In fact a heather moorland managed for grouse tends to form a monoculture of heather in its most vigorous and competitive phase, with occasional interruptions by species which form part of the regenerating pioneer community. The result is a uniform microenvironment and, other than in the wet slack areas, a severe restriction on associated species. The conservation value of a small area of Calluna monoculture is therefore limited.

However, in the example of the North Yorks Moors, the sheer size of the moor and its management means that nesting habitats can be created for golden plovers, merlins, and short eared owls and the cover gives shelter to large populations of the prey species of some of the carnivorous birds. The conservation value of the heather moorland of the North York Moors therefore lies in their physical extent as a relatively undisturbed habitat block (Brown, 1985 pers. comm.).

The upland areas of Britain recognised as Less Favoured Areas (LFA) under EEC Directive 72/268 are areas with poor land, below average output and a low or declining rural population (Rogers et al., 1985). Under this designation they are eligible for per capita stock subsidies and other special grants. These extend the provisions of the 1946 Hill Farming Act and the 1947 Agriculture Act, which were designed to assist in rehabilitation of hill land and increase production of home-grown foodstuffs after the war. The aim of the LFA programme is to recognise the comparative harshness of the upland environment and compensate for the competitive edge of lowland farmers. In practice, the subsidies may be 20 - 100% of the farmer's income (Allaby, 1983). Much of the change in upland agriculture has occurred as hill farming, which relies on open rough grazing, declines and is replaced by a more upland type of agriculture, where most of the land is enclosed and occasional feed crops are grown.

The direct conversion of moorland to higher quality grazing land carries a government subsidy of up to 70% of the cost of field drainage, or 50% of the cost of improving the grassland and allows further financial advantage through keeping larger numbers of stock which qualify for headage payments. The move towards capital intensive farming has meant that manual labour is being replaced by machines (CNP, 1985). The shortage of labour has been a factor in the cessation of burning as a form of management on heather moorland.

Controversy over the reclamation of moorland for agriculture reached a peak with the public debate on the continuing loss of moorland to agriculture on Exmoor in the 1960s and 1970s, which prompted the Porchester report of 1977 (see MacEwen and MacEwen, 1983). Parry et al. (1981) asserted that the problem was not confined to Exmoor and found similar results for three other areas. By extrapolation Parry suggests an average rate of enclosure and reclamation of moorland of 5000 ha. per year in England and Wales and this was confirmed by further detailed work (see for example, Parry et al., 1982).

Reclamation for agriculture is opposed by both the nature conservation and the amenity lobbies although the two do not always agree. Both aim for maintenance of the open moorland landscape, in which people can "hear and smell the wind, and listen to the cry of birds, while, briefly, we forget the roar and stench of the traffic of industry and commerce" (Allaby, 1983). The mismatch between the desire to preserve this dream, for which the National Parks were designated, and the reality of its projection onto the changing agricultural life of the uplands leads to an inevitable conflict of interests.

In 1942 the Scott report (Ministry of Works and Planning, 1942) on Land Utilisation in rural areas stated firmly that "there is no antagonism between use and beauty" and the report believed that "the best way of preserving the countryside in anything like its traditional aspect is to farm it" (MacEwen and MacEwen, 1983). The 1968 Countryside Act required the National Park Authorities to have "due regard to the needs of agriculture and forestry and to the economic and social interests of rural areas" and most parks have initiated Upland Management Schemes in response to the conflict between farming and recreation (CNP, 1985). In 1974 the Sandford Committee (Department of Environment, 1974), set up to review how far the National Parks were fulfilling their purpose, recognised the continuing conflict between agriculture and other uses. The report recommended that where recreation and conservation conflict, conservation should take priority. In practice the necessary extension of planning controls on agriculture was rejected by the Government (Rogers et al., 1985).

Planning for informal recreation needs an overview of a wide area as a series of minor land use changes may have a serious cumulative effect. Visitor pressure causes a wide variety of problems ranging from footpath erosion and the risk of accidental fire through damage to walls, fencing and farmland to the irony of ruining an area of natural scenic beauty by too many people coming to see it. The best management strategies attempt to temper the demands for recreation to the ability of the landscape to absorb them rather than automatically matching supply of facilities to the demand (NYMNP, 1981b).

To summarise, the management problems in the British uplands stem from a basic clash of interests between the politics and economics of agriculture, conservation and amenity. These are most apparent in the National Parks, where statutory rights exist for all parties.

Management for recreation in all upland areas centres on the maintenance of a sense of wilderness and an appropriate balance of moorland, woodland and farmland habitats. This in turn depends on the maintenance of traditional labour intensive agriculture. Management for wildlife conservation aims in most cases to protect specific sites from damage and in the case of moorland, to keep large expanses of heather moor intact and well managed, by the traditional, labour intensive methods.

The availability of agricultural grants, particularly through the Common Agricultural Policy (CAP) of the EEC and advice on their individual applicability by the Agricultural Development Advisory Service (ADAS) have initiated and confirmed changes in agricultural practices in the uplands. These have lead to a loss in the area of open natural and semi-natural moorland, and a decrease in management intensity in the remaining areas. Although there are some areas of overlap the management requirements of each land use appear to be basically incompatible.

Some kind of priority ordering must be written in to the management programme for each area of upland or moorland where these conflicts exist. Detailed and accurate knowledge on the vegetation communities present, the way in which they are changing and the factors effecting this change is an important base for such a programme.

Parry et al.(1982) used historical air photographs and maps to calculate the size of fluctuations in the boundaries of agriculture, forest and moorland over time. Black and white and false colour infra-red photography are already in routine use in a number of National Parks and formed the basis for the Porchester maps on Exmoor (Curtis and Walker, 1982). Satellite remote sensing, backed by suitable ground survey, has a unique potential for providing timely, regular and comprehensive data on ground cover at relatively low cost. Experimental work has been initiated on the use of Landsat MSS and TM data in the Exmoor, Peak District and North York Moors National Parks.

As set out in chapter 1, the scientific objective of this thesis is to examine the relative importance of spectral, spatial and temporal resolution as features of remotely sensed data for the moorland environment. The practical objective is to determine whether satellite remote sensing is a practical source of information for management of upland areas, particularly heather moorland.

3.4 The North York Moors.

This thesis concentrates on the North York Moors in northern England as a type example of the moorland community in Britain and of the general problems described in section 3.3. The North York Moors National Park was designated in 1952, its extent is shown in figure 3.4. The moors were selected as a test area for three reasons.

Firstly, the area is easily accessible. This was important as repeat visits were anticipated throughout the year. Officers of the North York Moors National Park have initiated a series of experiments on the ecology of the heather moorland, a number of which are concentrated on one estate. This area is used as a test site for detailed work. The site is discussed in detail in chapter 4.

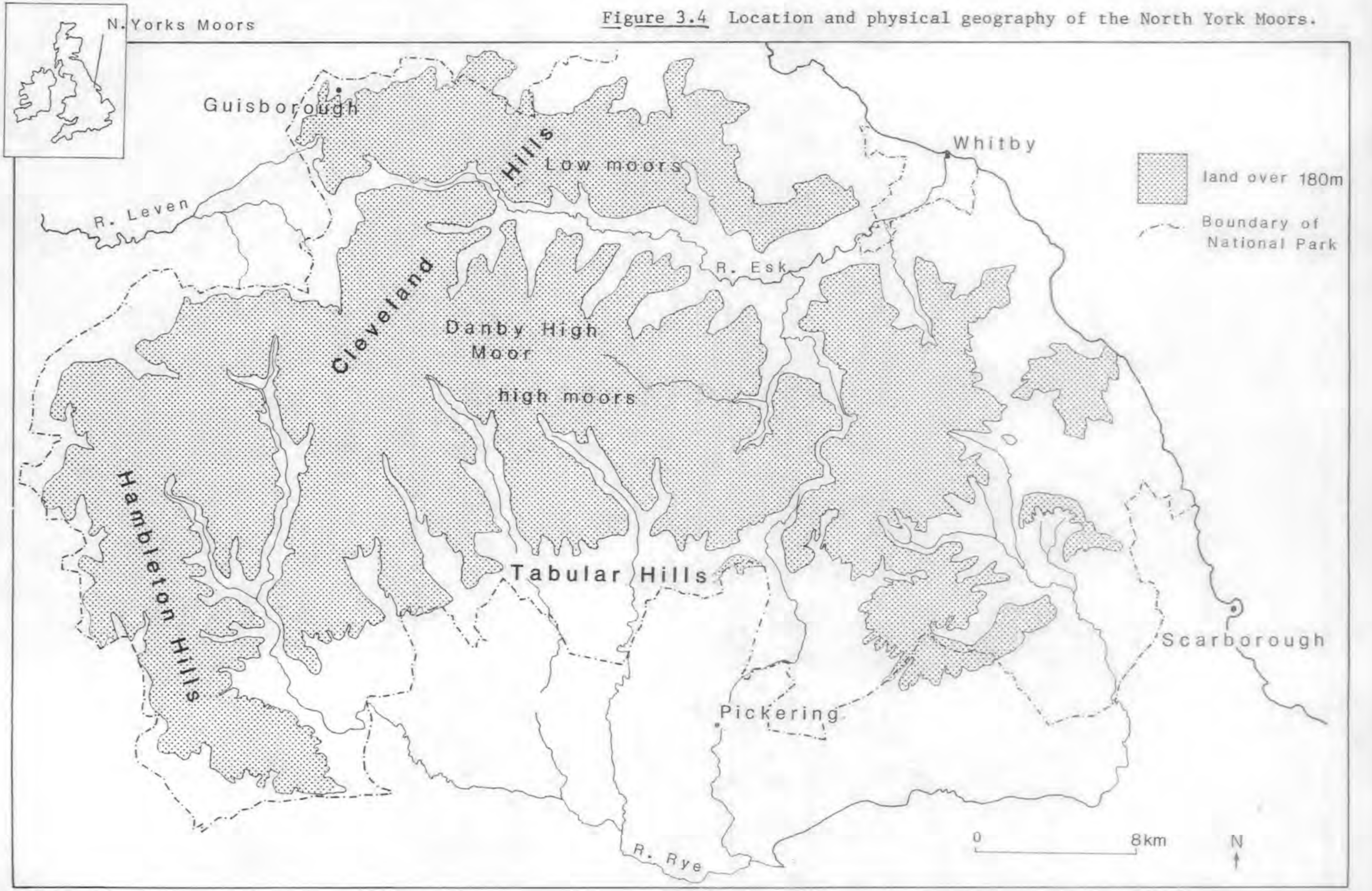
Secondly, the moors are topographically and vegetationally simple. The North York Moors were selected over the Northumberland moors for this reason. The moors consist of a central plateau, where Calluna vulgaris is dominant, and the bracken covered slopes which surround it. Much of the heather is in some kind of burning programme and apart from the wet slack areas there are few associated species. In the light of this simple structure it may be optimistic to expect that the results from this thesis will be of equal accuracy when applied to areas of greater topographic complexity or greater specific diversity.

A decisive final factor was the initial and continued interest shown in the project by officers of the North York Moors National Park.

3.4.1 Physical Environment

The physical extent of the North York Moors is clearly defined. They rise

Figure 3.4 Location and physical geography of the North York Moors.



sharply from the Vale of York in the west, the Vale of Pickering to the south and the Tees valley to the north (figure 3.4). The eastern boundary is the sea, with a 26 mile cliffed coastline within the National Park. The central high plateau of the moors is formed by the Cleveland Hills, and is separated into the low moors to the north and the high moors to the south by the east-west dissection of the Esk valley. The Tabular and Hambleton Hills to the south and west are lower and support a mix of farmland and moorland. Figures 3.5 and 3.6 show the solid and drift geology of the moors. The high moorlands, which support most of the *Calluna*, are formed by the Ravenscar series of sandstones and shales (NYMNP, 1979). Compared to other upland moorlands of northern England, Snowdonia and Scotland, the North York Moors are low-lying and dry, averaging only c.100cm of rain per year.

Figure 3.7 summarises the successive stages by which man cleared the area and allowed the heather to establish. Further details are available in Simmons *et al*., 1982). Were the current burning management to cease, the open moorland would most probably revert to deciduous woodland (J. Innes, pers. comm. 1985).

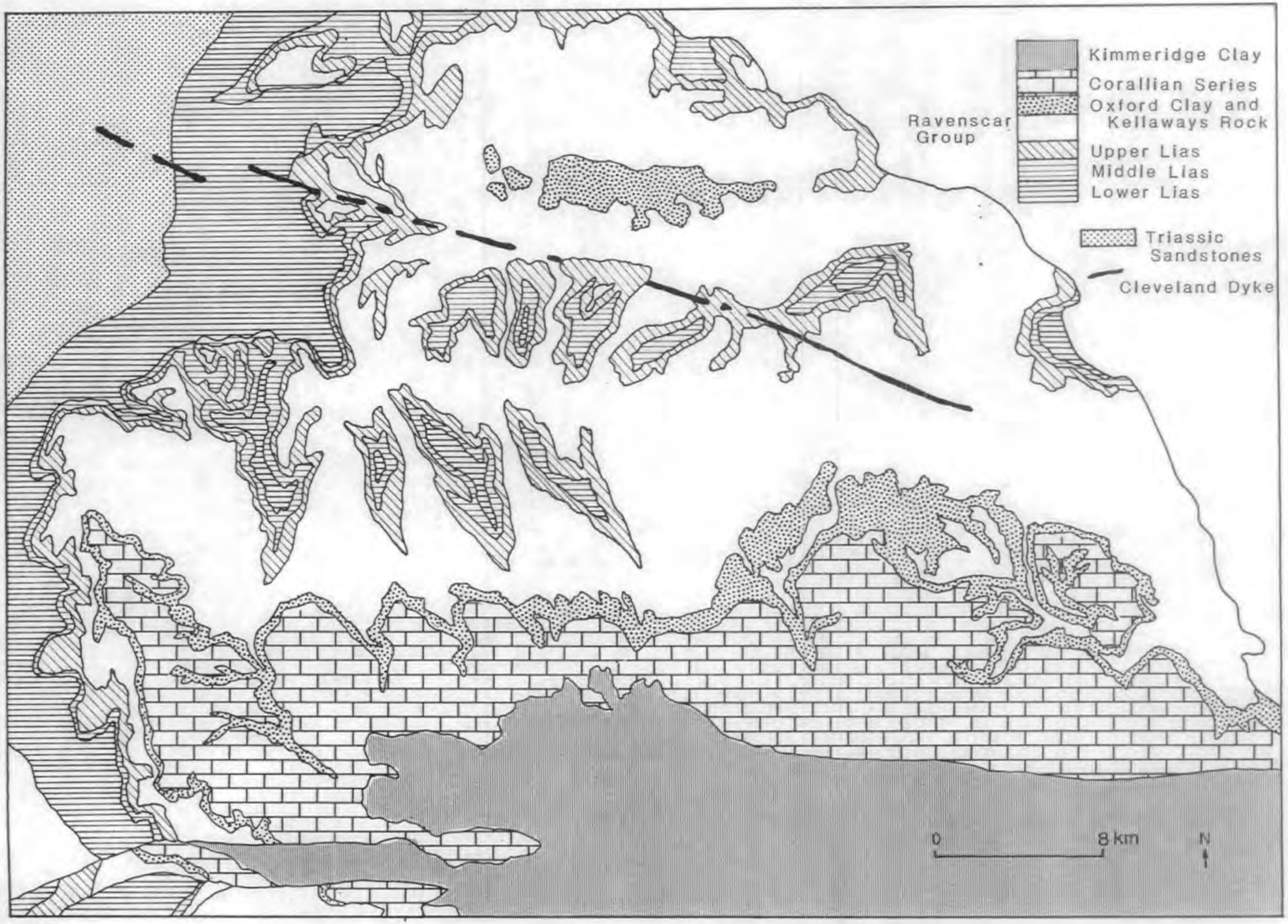


Figure 3.5 The geology of the North Yorks Moors. After NYMNP (1979).

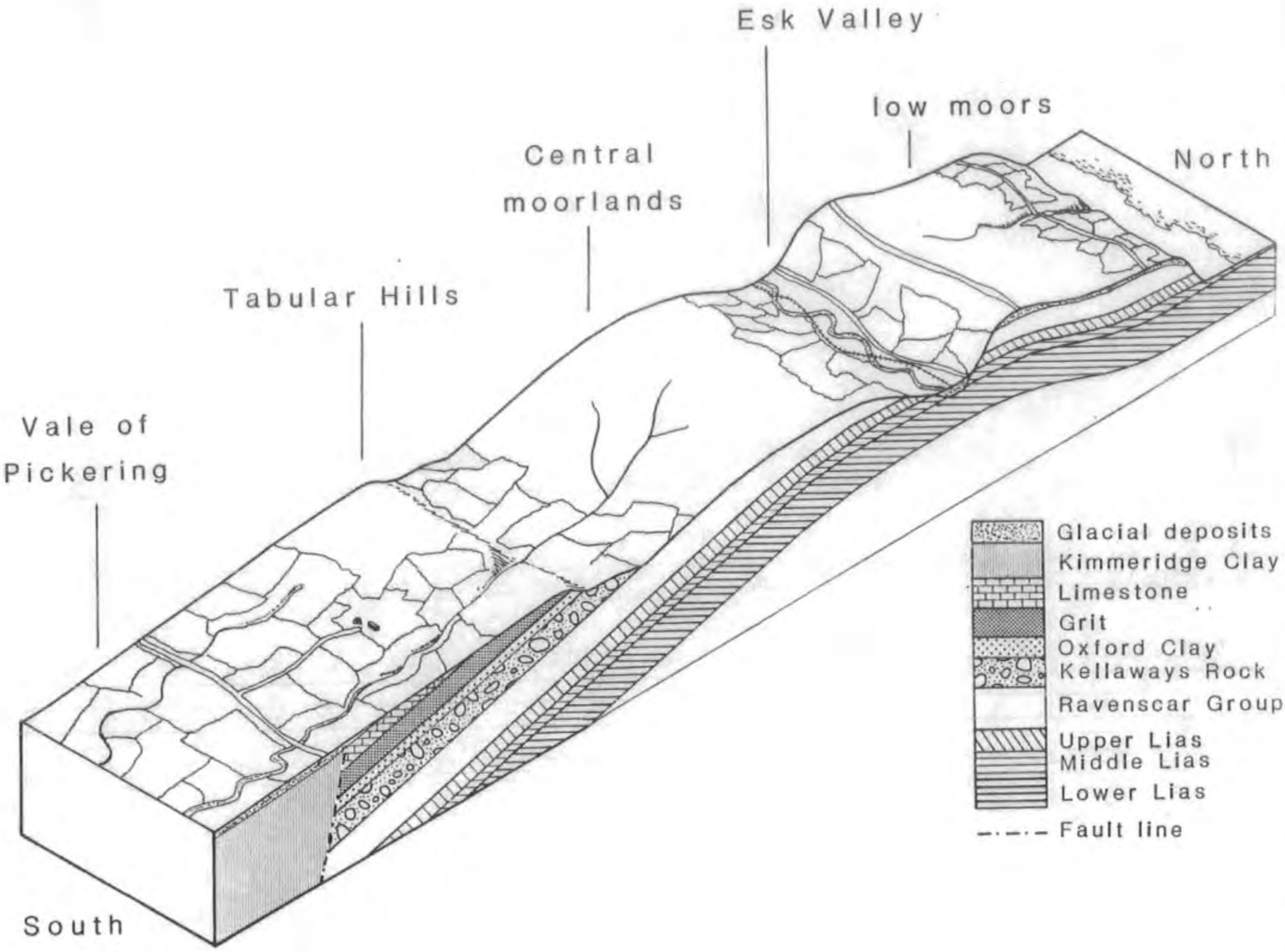


Figure 3.6 The geology of the North Yorks Moors - cross section. After NYMNP (1979).

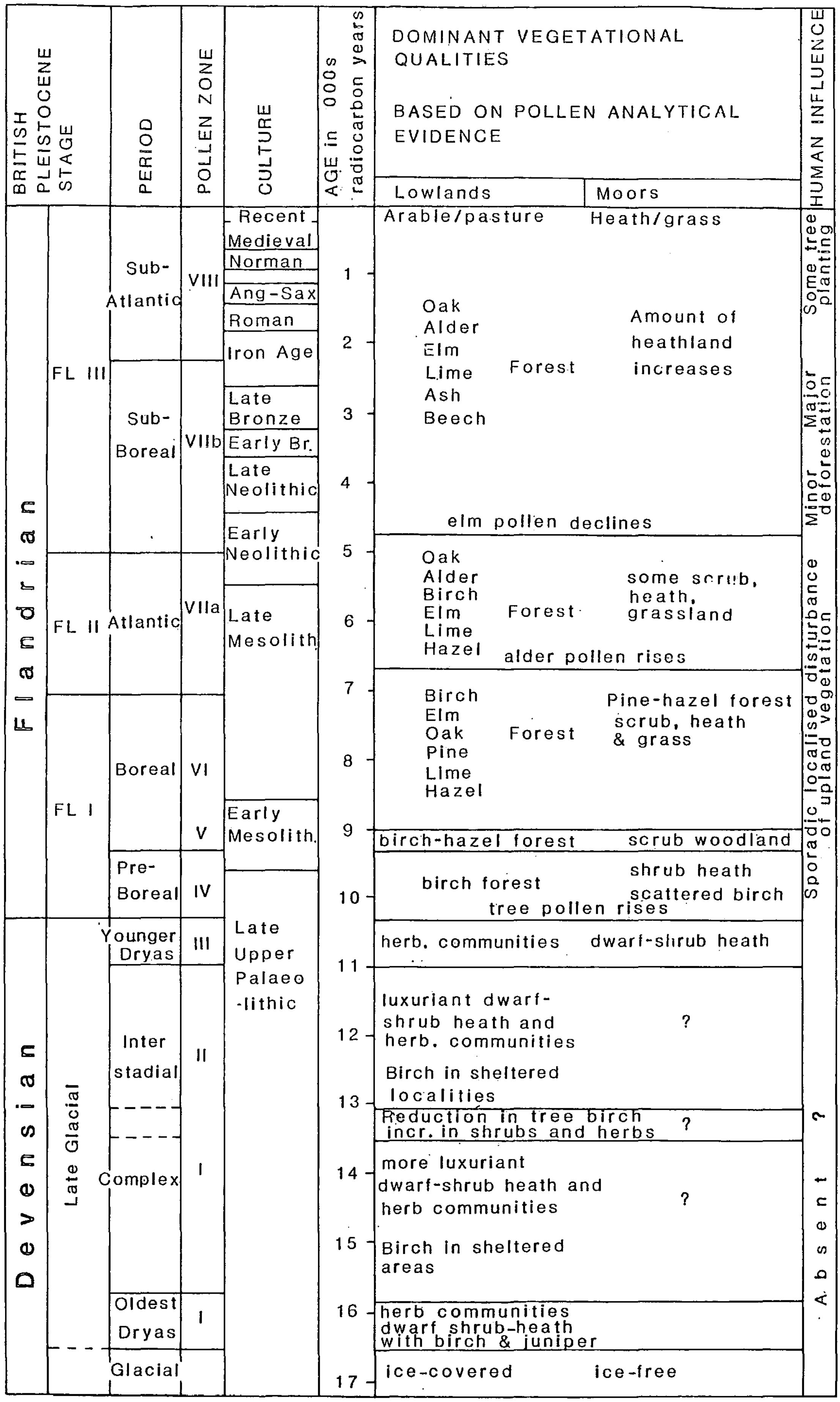


Figure 3.7 A schematic view of chronology, terminology and vegetational change on the North York Moors. After Simmons et. al. (1982).

3.4.2 Management problems

The management problems found in the North York Moors reflect the general pressures on resources discussed in section 3.3. A series of discussion papers on management issues has been published by the North York Moors National Park prior to a statutory revision of the National Park Plan. The following descriptions are drawn largely from these documents.

The National Park identifies three main processes which bring about moorland change (NYMNP, 1982).

i. Direct loss through conversion to agriculture and forestry.

ii. Bracken encroachment onto the heather moor.

iii. Direct loss or degradation as a result of catastrophic events such as pipeline disturbance or accidental fires, or changes in the intensity of management within the heather moor.

3.4.2.1 Direct loss to agriculture or forestry

Table 3.3 lists the amount of land deemed suitable for conversion to agriculture or forestry on the North York Moors. Recent agricultural reclamation has been concentrated on the southern fringe of the Park. Figure 3.8, compiled from the historical work of Parry et al. (1982) summarises the nature and direction of changes between agriculture, moorland and forestry. A detailed breakdown of the speed and duration of such change is given in Parry et al. (1982). Information from satellite data should allow continued inventory and monitoring of the moorland boundary and build on this historical base.

The National Park Committee is required by section 43 of the Wildlife and Countryside Act (1981) to produce a map of the Park, showing "any areas of moor or heath, the natural beauty of which it is, in the opinion of the authority, particularly important to preserve". Recent additions to the act (1985) extend the categories to "any area of mountain, moor, heath, woodland, down, cliff or foreshore". The map is to be updated at regular intervals of not more than five years. On the North York Moors the term

	Area (miles^2)	% of open moorland
Land suitable for afforestation	167.0	85.0
Land suitable for agricultural conversion	65.6	33.0
Land suitable for agricultural conversion but not afforestation	6.5	3.3
Total area suitable for conversion	171.5	88.3

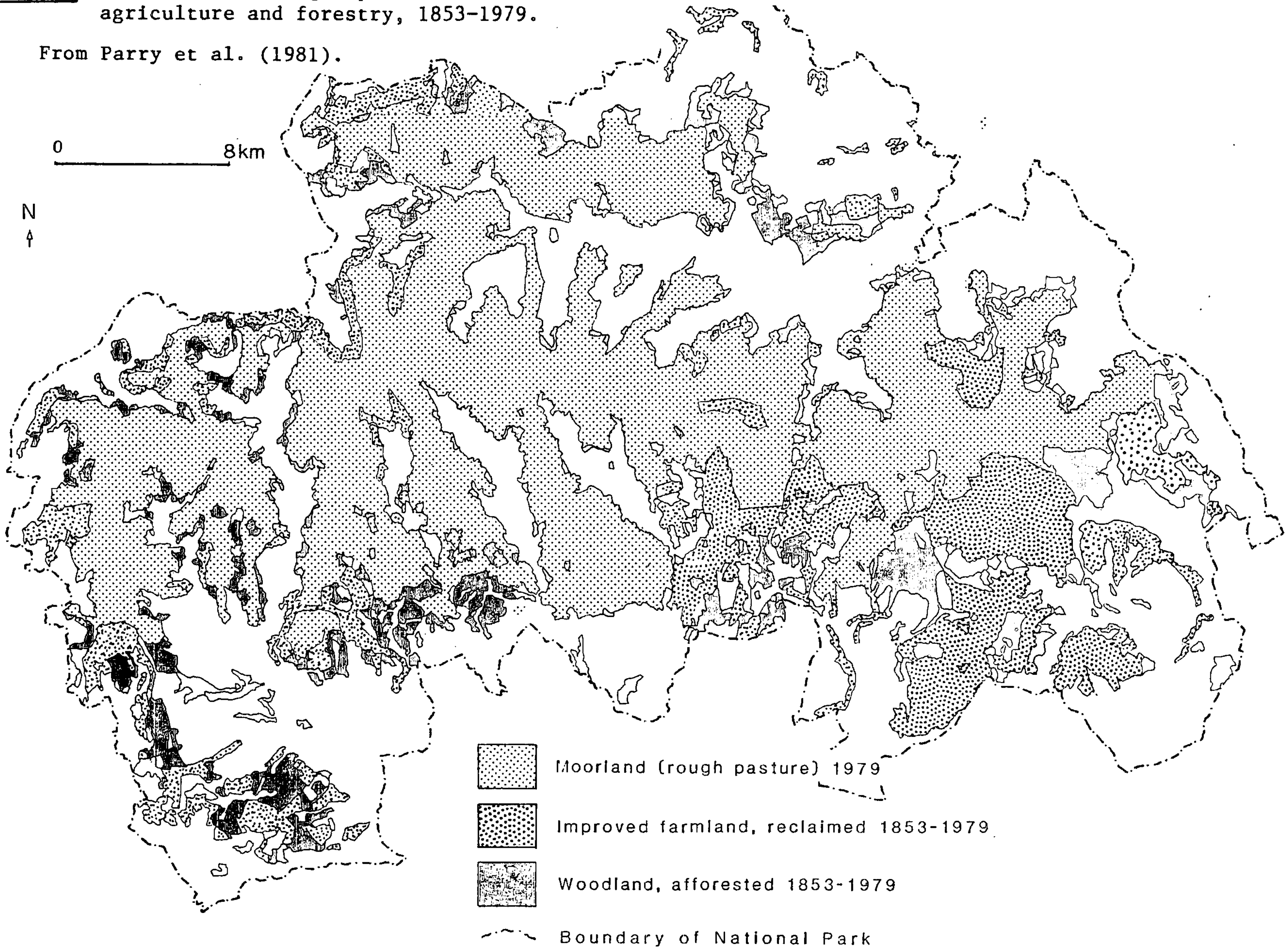
Table 3.3a Areas of moorland in the North York Moors National Park suitable for conversion to agriculture or forestry

		miles	% of 1950 total	% of whole park
Moorland area	1950	261.3	100.0	47.3
	1984	193.3	74.0	34.9
Change 1950-84				
to agriculture		19.3	7.4	-
to forestry		48.0	18.3	-

Table 3.3b Conversion of moorland to agriculture and forestry in the North York Moors, 1950-1984. Data from NYMNP (1982, 1986).

Figure 3.8 Conversion of rough pasture on the North Yorks Moors to agriculture and forestry, 1853-1979.

From Parry et al. (1981).



"natural beauty" is taken to mean areas of importance for any combination of natural history, visual amenity, archaeology and recreation.

The scale of mapping needed to identify these habitats is compatible with that needed to monitor the fluctuation of the moorland/agriculture boundary. In addition, other natural constituents of the moorland, particularly the bracken stands and the areas of cotton grass which mark the deep peat beds should be isolated at this level. The ecological importance of the bracken stands is discussed below. A number of the deep peat beds are SSSIs. It is important to maintain an inventory of such wet areas as they contain most of the faunal and floral diversity of the moors.

The problem of direct loss of moorland to agriculture is likely to remain as an environmental and political issue. However, future conversion of moorland depends on the condition of the vegetation and the soils at the time and is largely an unknown quantity. Proposals for the conversion of moorland to agriculture or forestry must go through statutory channels of notification, consultation and negotiation. The North York Moors National Park, while aware of the problem of direct loss, therefore identify erosion and "insidious degradation" within the moor as the most serious and immediate of their management problems (NYMNP, 1982; Maltby, 1980). These processes threaten not only the maintenance of the open moor but also its conversion to forestry or agriculture at a later date.

Two processes cause insidious loss and degradation of the heather moorland. The first is encroachment by bracken. The second is physical erosion and degradation of the substrate.

3.4.2.2. Bracken encroachment

Bracken is a normal constituent of open woodland, where it is in equilibrium with the surrounding species. When it is removed from shading and possible nutrient stress, as on the open unshaded moorland, its vitality increases dynamically and its competitive advantage is enormous. (Norton, 1982).

Bracken is found on the better drained soils on the steep slopes surrounding the moors, particularly the Riggs around the Esk valley. Once established it modifies the soil, reducing acidity and creating a nutrient rich frond layer. This hampers both germination from seed and vegetative regeneration of heather. Dense bracken stands also discourage recreational access and therefore increase recreational pressures on other areas (Norton, 1982). Bracken is toxic to stock if grazed, and has a poor associated flora and fauna (NYMNP, 1986). It can be argued that, once removed, bracken leaves a much improved soil with greater potential than adjacent areas of moorland. It also adds attractive colour to the landscape at certain times of year. However management for agriculture, recreation and conservation aims to maintain the open heather moor and bracken encroachment is a great economic nuisance.

Bracken shows a pronounced seasonality and a cylical succession of development. In the initial invading phase, individual bracken stems may appear away from the main community well in to the heather stands and this is the case in the North York Moors. Their growth is subsidised by the more vigorous established stands through a network of underground rhizomes. Once established, shading from the fronds works against the establishment of new heather seedlings, and the high litter density helps to exclude other species. An advancing front of bracken is typified by a gradual increase in density and height of fronds from the furthest advancing stems back towards the parent stands.

Watt (1955) described a cylical reinvasion of bracken by heather in the fenlands once the initial vigour of the bracken had declined. This situation is not apparent in the North York Moors as the reduced intensity of management of both bracken and heather create ideal conditions for its spread. The bracken rhizomes are buried relatively deep in the substrate and are not harmed in inadvertent or deliberate fires. Re-establishment and shading may occur before Calluna and other species have a chance to compete. Bracken has been controlled in the past by cutting for cattle bedding, but this has been largely discontinued.

The National Park are co-operating with the Ministry of Agriculture, Fisheries and Food (MAFF) in a series of experiments on bracken control. Different levels of treatment are applied to the bracken stands at various stages of development and subsequent regrowth is monitored.

The success of bracken control relies on good organisation of manpower and financial resources so that the sites which require treatment are located, the treatment is carried out properly and the follow-up procedure of checking regrowth is completed. The cost/benefit balance is particularly important where the farmer or landowner is undertaking clearance himself.

Under the current system of grant allocation landowners must contact the National Park for financial assistance in clearing bracken. Clearly a more active situation would be preferable, but regular ground or air based inventories of the Park are not practical. Satellite remote sensing could play an important role in bringing about a more active type of management by establishing the presence and vigour of existing stands and measuring the amount of regrowth following treatment. The requirements are to identify areas where bracken is strongly established, where natural advance is rapid, or where factors predisposing rapid advance exist. These include the presence of vigorous bracken stands adjacent to severe heather burns or disturbed land. Figure 3.9 shows how this sub-division fits into the separation of the major communities discussed in the previous section.

3.4.2.3. Surface erosion

Surface erosion is initiated and maintained by instability of the surface. This can be caused by recent controlled fire, old mining operations, pipelines, or visitor pressure. The biggest single threat however comes from the presence of extensive stands of over-age heather on the moors. Reductions in the labour force mean that the interval between successive burns has reached 25 years or over in some parts of the moor. After this point the heather is outside normal management practice. The over-age

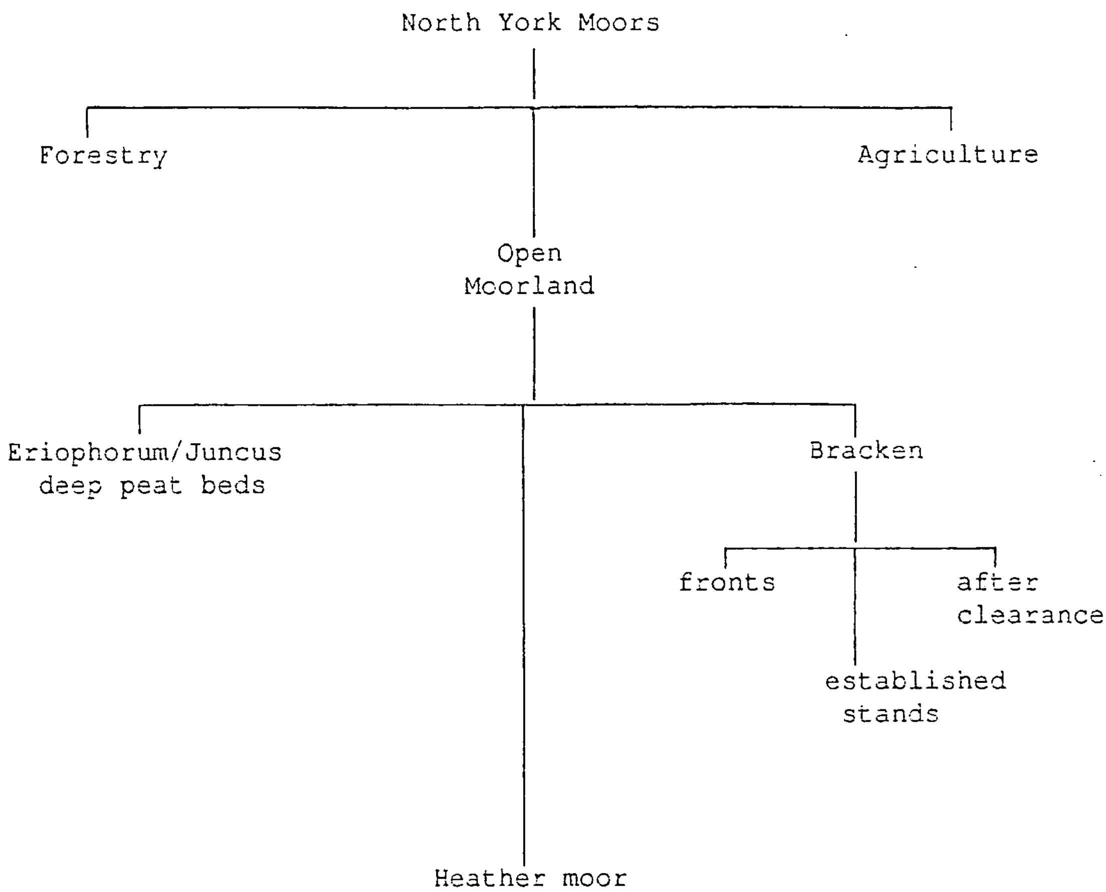


Figure 3.9 Plant communities to be identified on the North York Moors: major communities.

stands have a high proportion of dry, woody material and therefore have a high calorific value. They are unlikely to be burnt deliberately because the fire may get away from the keepers. Uncontrolled fires in these stands burn hotly and may reach into the peat, destroying the heather plants and exposing the remaining substrate to erosion by wind or water. A particularly dramatic example occurred at Glaisdale Moor, where extensive fires in the summer of 1976 exposed large areas of the deep peat reserves and burnt through to bare rock. The risk of uncontrolled fire and erosion is greatest where over-age stands occur in areas of intense recreational pressure, particularly along the Lyke Wake Walk.

An effective programme for controlling moorland erosion should therefore have two parts. The first, preventative, element, should identify stands of over-age heather which are a potential fire risk and, where appropriate, cut swathes to allow some controlled burning. The National Park have surveyed and categorised a number of moors on the basis of heather height. They found that 59.2% of the area surveyed carried heather over 25cm in height (underburnt), and this included 26.82% with heights above 40cm (outside normal management practices) (NYMNP, 1986). The second, monitoring, element would record the revegetation and stabilisation of areas exposed by any means, as a proportion of the substrate may still be exposed and vulnerable to erosion at the pioneer stage.

Together these measures amount to mapping the age distribution of the heather across the moor. The classes of heather stands needed for management at this level are summarised in figure 3.10. Their distinction in ecological terms is primarily on percent cover, biomass, surface stability and species diversity and can be referenced to the stages of Watt's cycle (figure 3.2). Clearly some of the stands on the moor will not fit neatly into a category and the definition of the cut-off points between classes will vary with current and preceding environmental conditions, the attitude of the gamekeeper and external pressures such as the amount of trampling.

The broad divisions between vegetated and non-vegetated areas can be made quite easily on panchromatic air photographs. It is however difficult to assess the amount of vegetation present in regenerating areas in these data and virtually impossible to differentiate accurately between established stands of different ages. Given sufficient spatial information, multi-spectral remote sensing may offer an effective alternative to conventional air photographs in this classification.

3.5 The role of remote sensing

The subdivision of the heather group is the finest level of detail needed over large areas of the moorland. Figure 3.10 therefore shows the full hierarchy of cover types which are important in management terms. forms. They cover relatively large contiguous areas, and are easily recognisable on the ground and from air photography. They should be separable in multispectral data with a minimum of spectral information. Each community is split into a number of classes. A more detailed vegetational description is needed to separate the elements of each community and they cover smaller areas. Intuitively, more detailed remote sensing data, in terms of spatial, spectral, radiometric, or temporal resolution is needed to resolve these elements of the community.

The importance of each element of the moorland community will vary with the severity and priorities of the management problem, as, for example, emphasis has swung from the continued loss of moorland for agriculture or forestry to the problems of erosion and degradation which occur within the heart of the moor. A single management task will therefore involve only a subset of the cover types of figure 3.10.

Most of the information at the lower levels is currently gathered for localised areas from detailed air photo interpretation and ground survey. This research will determine whether satellite remote sensing can provide a comparable or better level of information over extended areas.

The first step in all management problems is to separate, identify and locate the appropriate elements of figure 3.10 across the moors. This

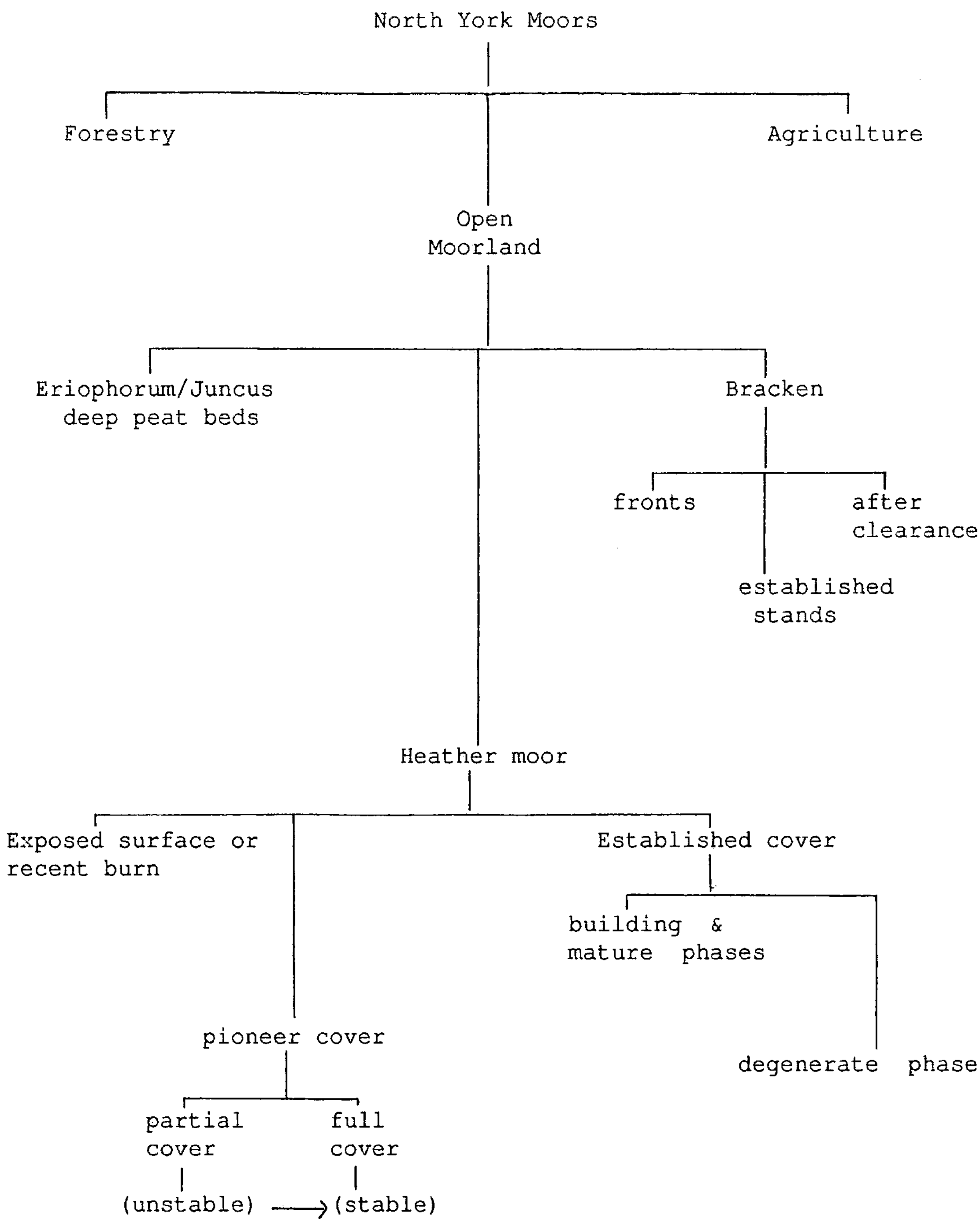


Figure 3.10 Plant communities to be identified on the North York Moors: major communities and divisions of heather moorland.

information will form a factual data base on the nature and extent of each part of the community. External contextual and interpretative knowledge can be added to the data base to generate information and management plans can be formulated from the whole. The main role of remote sensing will be to create and update the factual data base.

Strong parallels exist between the techniques used to describe the distribution of vegetation and those used in processing remotely sensed data. The distribution of vegetation and habitat is measured by a combination of discrete or continuous floristic and environmental variables. Where the vegetation is divided into exhaustive, discrete units, points which act as decision boundaries are identified on each variable. A point, quadrat or area is assigned to a given class on the basis of its position in relation to these boundaries and all other points. In other studies the vegetation is described by a series of ordinates, with no attempt to delimit sections of the continuum. Thus the cylical separation of heather may be described as a continual process of change in morphology, physiology, microenvironment and associated species, or as a series of overlapping but relatively discrete stages.

Where more than one variable is used to describe a vegetation distribution the superposition of the patterns described by each axis may confirm original groupings, suggest new ones, suggest different levels of patterning, or create groups across a previously continuous distribution. The clarity and utility of the groupings derived from such an analysis depends on the pertinence and independence of the axes.

In remote sensing imagery, the continuous and irregular distribution of vegetation on the ground is represented by a raster coordinate pattern. Each raster element or pixel has one or more recorded attributes, which are measurements of radiance at different wavelengths from the ground area defined by that pixel.

As shown in chapter 2, the wavebands used on earth resources satellite sensors are sensitive to certain features of vegetation canopies. It is therefore likely that clusters defined by the vegetation descriptors will have an approximate parallel in the spectral feature space, although the parallels between the vegetation descriptor and the waveband may not be direct or clearly predicatble.

The objective of applied remote sensing is to select the data set where the divisions in the spectral feature space are most closely associated with the important partitions in the vegetation space, in this case, the cover types of figure 3.10. This implies firstly, that the picture elements are of a size that is compatible with the spatial periodicity of the target; secondly that the spectral information is sensitive to the identifying characteristics of the vegetation; and thirdly, that there is sufficient dynamic range in the radiance recorded to distinguish subtle changes in radiance which are caused by changes in vegetation.

These requirements correspond to the spatial, spectral and radiometric resolutions discussed in chapter 2. Complex vegetation communities require a large number of variables for an adequate description of their distribution. In the same way requirements for resolution are expected to change with change in the floristic, environmental, or spatial complexity of the target and the amount of detail that is required.

The vegetation space has been outlined in this chapter and a more detailed and quantitative description follows in chapter 4. The practical aim of this work is, for each management problem outlined, to identify the set of remote sensing system parameters whose feature space most closely matches the vegetation space.

Chapter Four: Ground radiometer measurements from moorland vegetation.

4.1 Introduction

Chapter 2 described the way in which the reflectance and emittance of energy from plants is related to the physiological and structural features of the plant components and the plant canopy. Section 3.5 of chapter 3 broadened this to the proposal that stands which group together on vegetation and environmental variables will fall into similar clusters when defined by their spectral response.

This chapter examines the accuracy of this proposal by analysing reflectance measurements collected with a ground radiometer from a subset of the moorland vegetation types listed in figure 3.10. The specific aim of the analysis is to identify whether the critical divisions between vegetation communities at the ground are also made in their spectral response, and therefore draw preliminary conclusions on the feasibility of using multi-spectral remotely sensed data in the management of moorland areas. The work will also allow preliminary investigation of the relationships between vegetation descriptors and response in the visible and near-IR parts of the spectrum. Section 4.2 gives a general description of the vegetation at the test site, outlines the sampling methods used and gives a detailed summary of conditions at each sample point. Sections 4.3 and 4.4 outline the expected relationship between ecological descriptors and spectral response and the methodology of collecting ground radiometer data respectively. The ground radiometer measurements are presented and discussed in section 4.5 and the implications of the results are summarised in section 4.6.

4.2 The test site

The two levels of vegetation classification needed for management are summarised in figure 3.10 of chapter 3. At the upper level, agricultural land and forestry can be isolated from the open moor by their size, shape and location as well as their spectral characteristics. Similarly, in this area, the bracken is largely confined to the steep slopes which surround the heather moor. The most important management problems lie within the heather moorland, and identifying the elements of this class will rely almost completely on their spectral characterisation. The ground radiometer programme therefore concentrates on this "hardest case" of separating and identifying the exposed surfaces, the stages of recolonisation and growth of heather and the wet flushes within the heather moor.

The test site is Danby High Moor, in the centre of the High Moors (figure 4.1), where most of the components of the moorland community are present in a small area. The cyclic succession of Calluna and its management by fire are the dominant characteristics of the vegetation over the whole of the moorland area, although there is some local variation due to the substrate and the intensity of management. Extensive field checking of the surrounding Glaisdale, Westerdale and Danby Moors confirmed however that the test site is a good example of the range and complexity of the community on the high moors.

Figure 4.1 shows the distribution of vegetation at the Danby Moor site. The map was compiled from a 1983 air photograph (figure 4.2) and fieldwork in the summer of the same year. The dominant cover types are exposed peat substrate, the stages of succession to a full heather canopy and established stands of Calluna. The presence of Eriophorum indicates a high water holding capacity in the substrate and at this site this is synonomous with a lens of deep peat. The pattern of vegetation at the site is largely determined by previous burning and there are sharp spatial divisions between different stands.

Because of the distinct spatial pattern it is tempting to consider each element of the patchwork as an equally distinct unit in ecological terms. In fact, each cell of the patchwork has sufficient features in common with a subset of the remaining cells for the whole set to form a continuum,

Figure 4.1 Distribution of vegetation at radiometer test area, Danby High Moor.

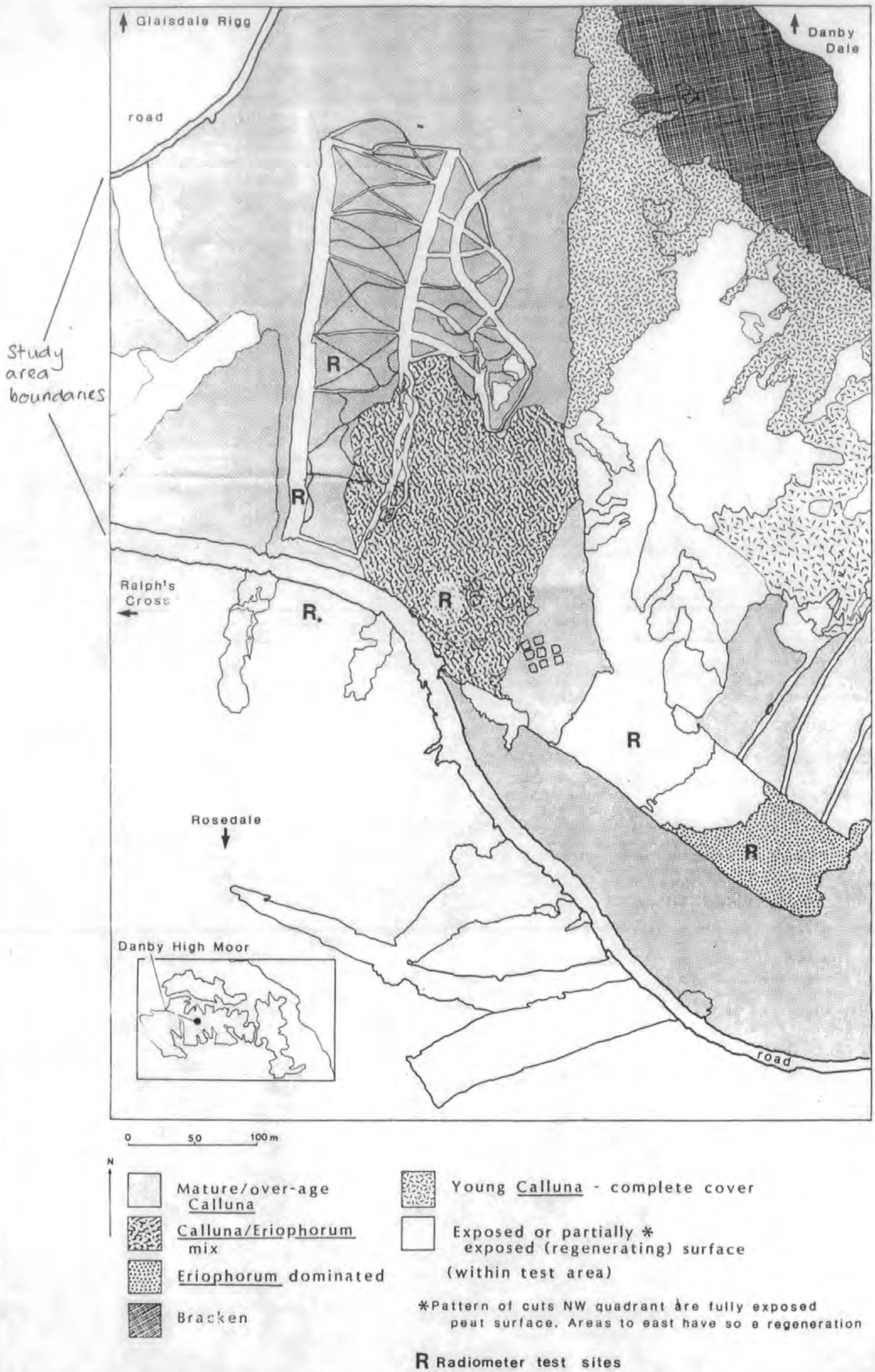


Figure 4.2 Vertical air photograph of radiometer test sites. See text and figure 4.1 for full description of vegetation distribution

which can be summarised into the phases of succession recognised by Watt (1955) and outlined in chapter 3. As noted in chapter 3, this use of Watt's division places artificial boundaries across a continuum in order to establish a classification for management purposes, when in fact the distribution of the sites "hovers tantalisingly between the continuous and the discontinuous" (Williams et al., 1966). Thus the sites selected for radiometer measurements are truly representative only of particular points along the continuum of canopy development, but are taken to represent the wider classes defined by Watt.

The sites selected for ground radiometer measurements are indicated in figure 4.1. They are an exposed peat surface, an area of rapid recolonisation by heather and Vaccinium, young and mature heather stands, an area dominated by Eriophorum and a mixture of Calluna and Eriophorum on the lens of deep peat. The "new burn" site appeared in the Spring of 1984 when a number of sites were burnt. These classes were selected as representative of the management divisions introduced in chapter 3. The particular sites were selected for the practical reason of ensuring that a full set of measurements could be collected as rapidly as possible.

The abundance of newly cut or burnt areas indicates the level of active management of the moor and thereby monitors progress towards undermanagement and the dominance of over-aged heather. This is also the stage at which the peat surface is most vulnerable to erosion. An important first step in management is therefore to separate the completely exposed sites from those where some revegetation has occurred and the surface has greater stability. The newly burnt areas sampled here are mainly on the deep peat lens and therefore have had Eriophorum as a dominant or co-dominant. Some of the clumps of Eriophorum were apparently undamaged in the fire and have regenerated rapidly. In drier parts of the newly burnt sites there is some colonisation by Calluna and Sphagnum.

The swaths cut through the heather in the north-west of the site, exposing the peat surface, are part of a controlled burning experiment set up by the

National Park. Most of the vegetation was removed and burnt off site. There is localised patchy regrowth of grasses, Calluna and Vaccinium in the areas where some of the cut heather was left on site.

The central area of figure 4.1 is a complex of communities recolonising after fire. In general, the darker areas on the air photograph have a more complete vegetation cover and in most cases this is a mat of pioneer Calluna. Two areas are at an advanced stage of growth where full cover has been established. The heather here is growing vigorously and is about 15cms high. Regrowth has been relatively rapid at these sites as they are in a local drainage hollow which has a damper substrate than the rest of the central area. In the lighter toned areas to the south regrowth is less advanced and a high proportion of the area is exposed peat surface or bleached heather stems. Vaccinium is a local codominant with Calluna throughout these areas. There is some evidence for a lowering of the peat surface in the southern parts, but erosion by wind or water is not a serious problem in any part of the test site and colonisation has advanced rapidly over the research period.

The building stage of heather is absent from the test area but present on the moors immediately to the south and east. Virtually all of the established Calluna stands in the test area are under-burnt and large areas are outside normal management practice as defined by the National Park (NYMNP, 1986). The effects of uncontrolled fire in these stands are likely to be severe and the proximity of roads, car parks and a popular long distance footpath increase the risk of accidental fire.

Two types of over-age heather canopy are present in the test area. In the first the canopy is closed and virtually complete. In the second, the Calluna branches have fallen back to create an uneven gappy canopy. In the areas of deeper peat Eriophorum is present as an understorey and root base for this heather canopy. On occasion it becomes a major component of the upper canopy and this is visible in figure 4.2 as a light mottle on the dark heather.

The change west and north from the Calluna/Eriophorum mix to a more uniform heather canopy is clear in figure 4.2 and marks the edge of the deep peat area. In the area of sedges to the east, Eriophorum has become the main canopy component after fire. The plants are interspersed with pools of standing water, reduced but present even in very dry conditions. Stunted heather plants form a continuous understorey, rooting in the clumps of Eriophorum.

4.2.1 Detailed description of vegetation at the radiometer sample points.

A vertical colour transparency was taken at each sample point in the radiometer sites (see section 4.4 for sample method). This was enlarged by display through one lens of a Fairey additive colour viewer. A 5mm grid with 200 randomly located points was overlaid on the image (after Curran and Milton, 1983; Pinter et al., 1983). The cover type at each point was classified according to table 4.1. A full description of the test sites according to these classes is given in Appendix 1, together with examples of prints taken from the transparencies. Combining classes gives a description of the vegetation in the following terms:

a. The total amount of vegetation present, expressed as percentage cover. Vegetation height was also recorded to give an indication of biomass. Clipped samples were not taken.

b. The proportions of brown and green vegetation.

c. The species present and their relative proportions.

d. The type and amount of substrate visible.

e. An indication of the height and complexity of the canopy, as shown by the amount of shadow.

The substrate characteristics of

a. litter moisture (% by weight)

b. soil moisture (% by weight)

c. soil colour (Munsell chart)

d. soil organic matter (% loss on ignition) The last

1. Heather	i.	Green shoots and leaf
	ii.	Brown shoots and leaf
	iii.	Woody stems
	iv.	Flowers
2. Sedges	i.	Green shoots and leaf
	ii.	Brown shoots and leaf
3. Moss		
4. *Vaccinium*		
5. Leaf litter		
6. Substrate		
7. Shadow		

Table 4.1 Classification of canopy components at radiometer sites, as identified from colour transparencies (see text, secn. 4.2.1).

were later discarded, as the substrate at all sites was peat or peaty podsol with an organic content of over 90%.

Table 4.2 and figure 4.3 summarise the characteristics of each site in terms of these variables and demonstrate the degree of variation in surface cover within each pre-specified test site (see also Appendix 1). They also show that there is no single variable that discriminates between all groups. As suggested in chapter 3 a clearer separation is possible where two or more descriptors are used and this is shown in the plots of figure 4.3. Figure 4.4 is the result of a cluster analysis on the vegetation and substrate variables. The clustering was produced through the MIDAS statistical package, using centroid clustering and the correlation coefficient as the distance parameter. In this method each cluster is characterised by the average value of each variable on the component sites. The distance criterion combines cases and clusters which have the highest correlation across the variables. The centroid of the cluster is then redefined to include the characteristics of the new case.

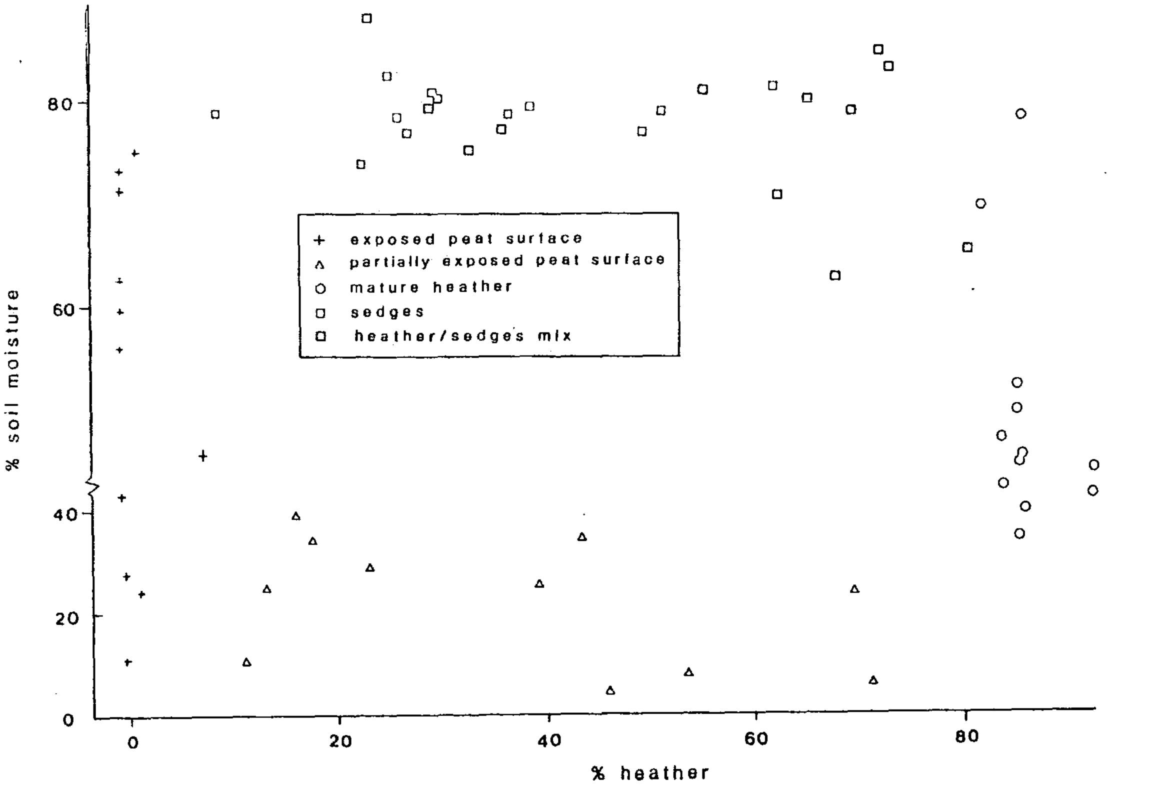
The combination of centroid clustering and correlation gives slightly better results, in the sense of meaningful clusters and reduced chaining, than any other combination of centroid or nearest neighbour clustering with Euclidean, Euclidean squared and correlation as distance measures. In particular, the centroid clustering brings the regenerating sites into one group and separates them from all other sites.

In statistical terms a cluster analysis on these data is not valid, as the percentage cover figures form a closed number system, with concomitant problems of correlation between variables. As a descriptive exercise however the analysis gives a useful summary of the main groups of vegetation at the site.

The two major clusters represent fully or partially exposed surfaces and established vegetation cover respectively. Samples from the exposed peat surface and the regenerating area are separated in the former and the established vegetation cluster also contains two subsidiary groups. The

		Calluna	grasses & sedges	total vegetation	substrate + litter	soil moisture
		% cover	% cover	% cover	% cover	%
Exposed peat	$\bar{x}$	0.93	2.84	11.10	86.98	51.06
surface	c.v.	2.45	3.16	0.25	0.15	0.39
Partially vegetated	$\bar{x}$	34.31	0.55	41.41	43.80	26.52
peat surface	c.v.	0.68	3.18	0.61	0.49	0.58
Mature	$\bar{x}$	86.89	0.28	87.20	0.00	49.28
heather	c.v.	0.04	1.57	0.03	-	0.69
Sedges	$\bar{x}$	34.54	54.14	89.61	4.42	78.81
	c.v.	0.43	0.24	0.06	1.54	0.03
Sedges/heather	$\bar{x}$	56.33	23.57	80.84	1.12	77.07
mix	c.v.	0.35	0.79	0.07	2.31	0.10

Table 4.2 Summary statistics, mean ($\bar{x}$) and coefficient of variation (c.v.) of canopy and substrate variables at radiometer test sites, August 1983. Figure 4.3 shows the characteristics of the test sites as defined by a second group of descriptors.



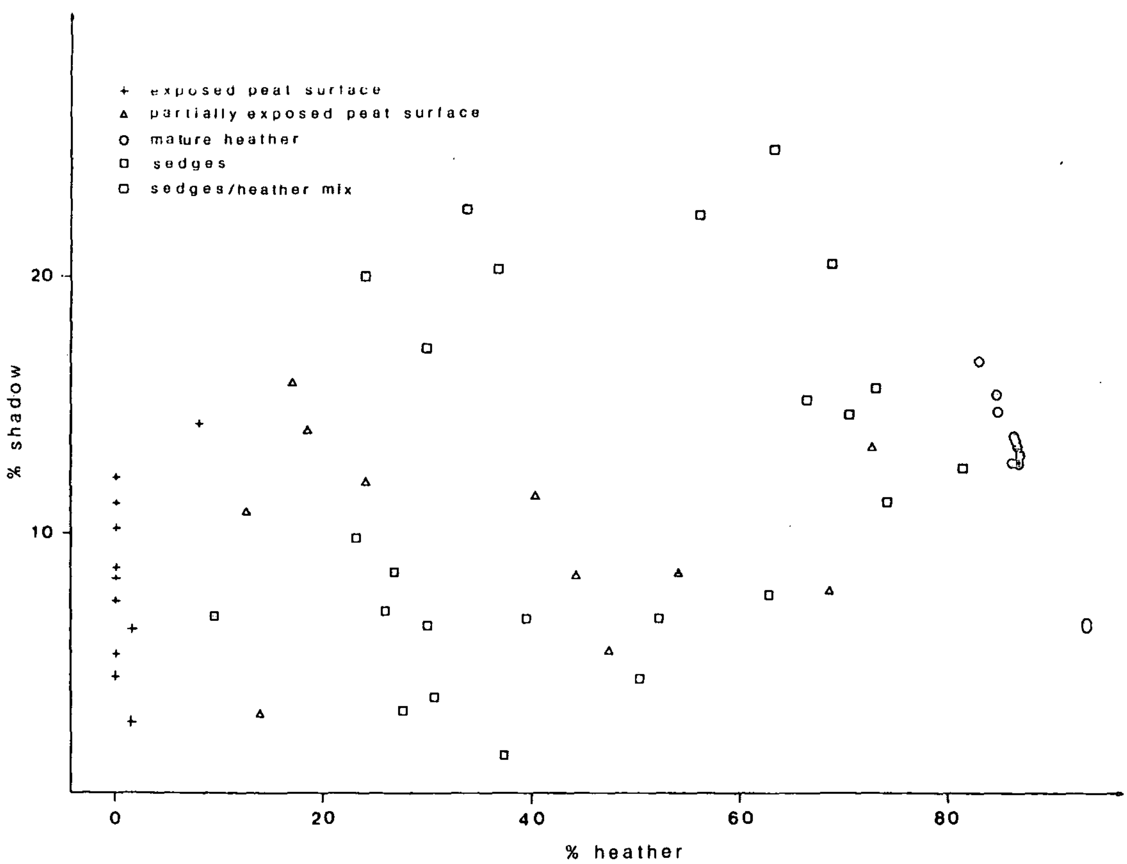
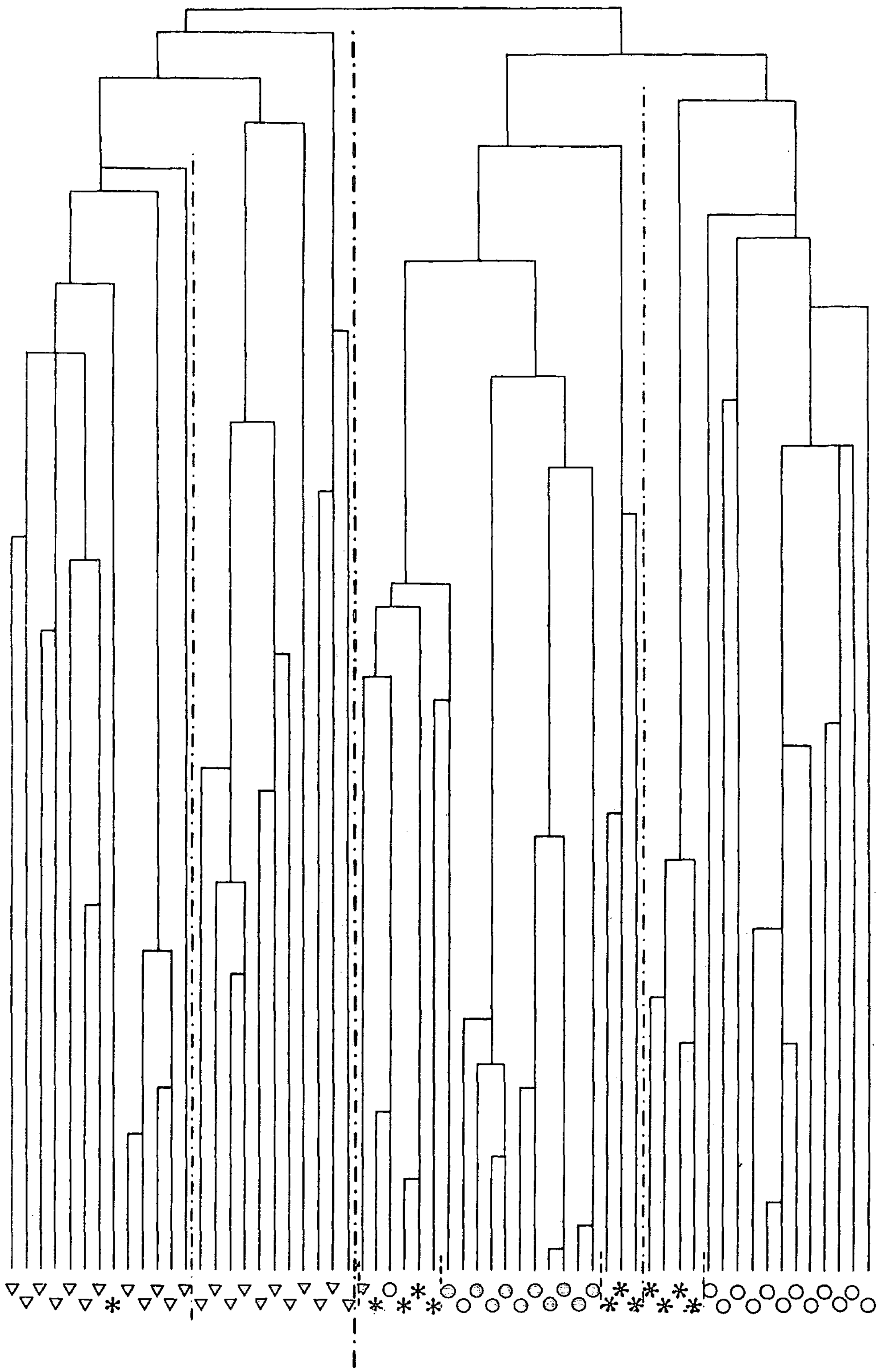


Figure 4.3 Distribution of radiometer test sites in feature space described by vegetation and environmental variables. Data collected August 1983.



▽ Exposed peat surface
▽ Partially exposed peat surface (regenerating)
* Calluna/Eriophorum mix
○ Mature Calluna
○ Eriophorum

Figure 4.4 Cluster analysis of radiometer test sites as described by vegetation variables

See text for details

first is predominantly mature and over-age heathers, the second is predominantly sedges. The mixed Calluna/Eriophorum sites are assigned to one or other of these groups on the relative proportions of heather and Eriophorum present.

Figures 4.3 and 4.4 demonstrate the ideas proposed in general terms in chapter 3, i.e., that a vegetation pattern at the ground can be characterised by the distribution of a number of descriptive variables, and that a larger number of variables produces a clearer and more meaningful isolation of classes.

4.3 Vegetation characteristics and spectral response

The variables used to describe and isolate the test sites reduce to the amount and type of vegetation present and the type and water status of the immediate substrate. The aim of the ground radiometry programme is to determine whether the distributions and distinctions of the test sites on these axes persist when the sites are described by their spectral response.

As noted in chapter 2, although the hemispherical reflectance of each canopy element depends on its physiological and structural features, the response of the canopy as a whole is best predicted by its Leaf Area Index (LAI), or the ratio of the one-sided leaf area to ground area (Curran, 1983). There will be variation in response within the canopy as the response of individual elements is influenced by their position in the canopy, their age and health, local environmental conditions and seasonal change.

This section discusses briefly the extent to which the variables used in section 4.2 correspond to the features of the plant and the plant canopy which influence spectral response directly, as this determines the degree of similarity that can be expected between the two distributions.

4.3.1 Species content of stand and the amount of shadow.

The leaf structure, pigmentation and canopy structure of each of the main moorland species are substantially different. The differences in response between the full canopies of the moorland species are therefore expected to be greater than the variation found within each species. The basic ecological indicator of species identification should therefore also be important in isolating stands by their spectral response.

The amount of shadow in the canopy would not normally be recorded in an ecological survey but was noted here as an indication of the height and complexity of the canopy. In fact the amount and intensity of shadow in the canopy can have a considerable effect on radiance (see Wardley and Miltón (1985); Kirchner et al. (1981, 1982) for discussion). In this environment the difference in the amount and the intensity of shadow between stands is unlikely to be an independent influence on spectral response, but will be tied to the overall difference in response between canopies of different species.

4.3.2 Amount of vegetation and the effect of the soil background.

"Amount" includes the percentage cover of vegetation and the total biomass of the stand. Both definitions are important ecological descriptors in the moorland community. Total percentage cover is sufficient in most cases to discriminate between the recolonising areas and the established stands and it is an important indicator of surface stability within the regenerating areas. An indication of biomass, particularly the amounts of green and woody vegetation, is needed to isolate the heather stands of different ages.

In most incomplete canopies percentage cover is directly related to LAI and will therefore be similarly related to the spectral radiance of the canopy. Where the spectral contrast between the vegetation and the soil is low however, the relationship between radiance and vegetation amount will be weak and critical differences in vegetation amount may not be registered in the spectral response.

It is possible to deduce and remove the soil contribution empirically (eg.

Tucker and Miller, 1977) and a number of linear combinations of wavebands have been developed in an attempt to reduce its complicating effects (see, for example, Colwell, 1974a, 1974b; Richardson and Wiegand, 1977; Frank, 1984; Crist and Cicone, 1984). In the moorland environment the near-IR wavebands are expected to differentiate between the dark peat soils and vegetation more clearly than the visible wavebands (see Curran, 1983). Curran also found that wet (darker) soils decreased both the red and the near-IR response of heather dominated areas and dry soil increased it.

Tucker (1977a, 1977b) found the overall relationship between biomass and spectral response in simple grass canopies to be asymptotic, although he also (Tucker, 1979) found strong linear correlations between radiance in the red and near-IR wavelengths and total dry biomass, dry green biomass and dry brown biomass in canopies of lower biomass. The form of these relationships for each canopy depends however on the relationshp between LAI and spectral reflectance and that between biomass and LAI (Curran, 1983). The spectral response of stands where LAI is not directly related to biomass, or where the canopy contains a high proportion of woody material, is positively related to biomass only when biomass is low. This has been demonstrated for heather by Curran (1986a), who found that the relationship between biomass and both LAI and spectral response was a function of the canopy morphology. The relationships were strong and positive for the developing canopy, weak in the mature stage and negative at the degenerate stage, where the canopy opens out and a high proportion of the total biomass is woody supporting tissue. The data of table 4.2 and figure 4.3 make a distinction between the young and the old or degenerate stands on the basis of the amounts of green and brown vegetation in the canopy. The results of Curran's work (Curram, 1981, 1986b) suggest however that different aged heather stands may have a similar spectral response in the visible and the near-IR bands.

A more detailed quantitative description of biomass and the canopy structure, particularly the LAI, as part of the ecological survey would improve the match between the ecological descriptors of section 4.2 and the expected spectral response of the canopies, although at least a rank ordering of the test sites can be made for each of these variables. The parallels between the two sets of axes suggest that with the important exception of some of the heather stands, the cover types which are separable in the vegetation feature space are likely to be so in remote sensing data. More importantly, a vegetation description which makes sense to the ecologist will have considerable correspondence with the variables that influence the spectral response of the canopy.

4.4 Ground Radiometry

A ground radiometer is a portable remote sensing instrument which allows the user to measure the reflectance of specific targets in the laboratory or the field. The radiometer can be hand-held or supported by a stand and may be used from the ground or a vehicle. The wavelengths that can be recorded are determined by the type of filters and detectors in the instrument.

Collecting ground radiometer data has become a routine part of remote sensing work. Much of the initial data collection was the logical extension of laboratory work to the complexities of field canopies and was undertaken in support of the Landsat programme (see for example, Tucker et al., 1975; Colwell, 1974a). Radiometer data are now used regularly to obtain information on the spectral response of natural and semi-natural environments (see, for example, Hardisky et al., 1983; Weaver and Wright, 1986) and have been used extensively in agricultural studies to assess the amount of useful yield and crop condition information in remotely sensed data (Aase and Siddoway 1981; Richardson et al. 1983; Everett et al., 1985). The effects of plant stress and the seasonal changes of radiance during growth have been addressed in particular (Jackson and Ezra 1985; Holben et al., 1983; Pinter et al. 1981, 1983). Radiometer data are also used in the laboratory to resolve ambiguities in the basic relationships between canopy variables and their effect on spectral response (Curran and Milton, 1983).

The Milton Multiband Radiometer (MMR) was used in this work as it is cheap, robust and suitable for transport and operation in the field by one person. The design and construction of the radiometer are described in detail in Milton (1980) and Milton (1982). Each radiometer consists of a sensor head, lead and analogue or digital recorder. In the field the instrument is supported by a stand so that radiance is recorded from the target in the four wavebands of this instrument. The angular field of view (FOV) of each detector in the instruments used in this work is 15^{o}. When mounted at a height of 2m, the sensor therefore views a circle approximately 1m in diameter. The surface components in this area do not contribute equally to the radiance recorded, experiments show that the central area can have a disproportionately high influence (Hancock, unpub and figure 4.5).

Two radiometers were used over the period of this work. The bandpasses of the first (MMR Mk I), approximate those of the Landsat MSS. The first near IR band is omitted in MMR Mk II and replaced by a blue waveband to simulate TM1. The relative spectral response curves for the two radiometers are given in figure 4.6.

Measurements of reflectance are collected by ratioing readings in each waveband taken alternately from the target and a reference surface, in this case a Kodak grey card as suggested by Milton (1980,1981), and standardising by the reflectance of the grey card in that waveband. Three sets of target and reference measurements are taken in each waveband at each sample point. The final measurement for the sample point is the average of the three reflectance measurements in each waveband, viz.

$$\frac{1}{3}\,(R_1 \times K_\lambda + R_2 \times K_\lambda + R_3 \times K_\lambda)$$

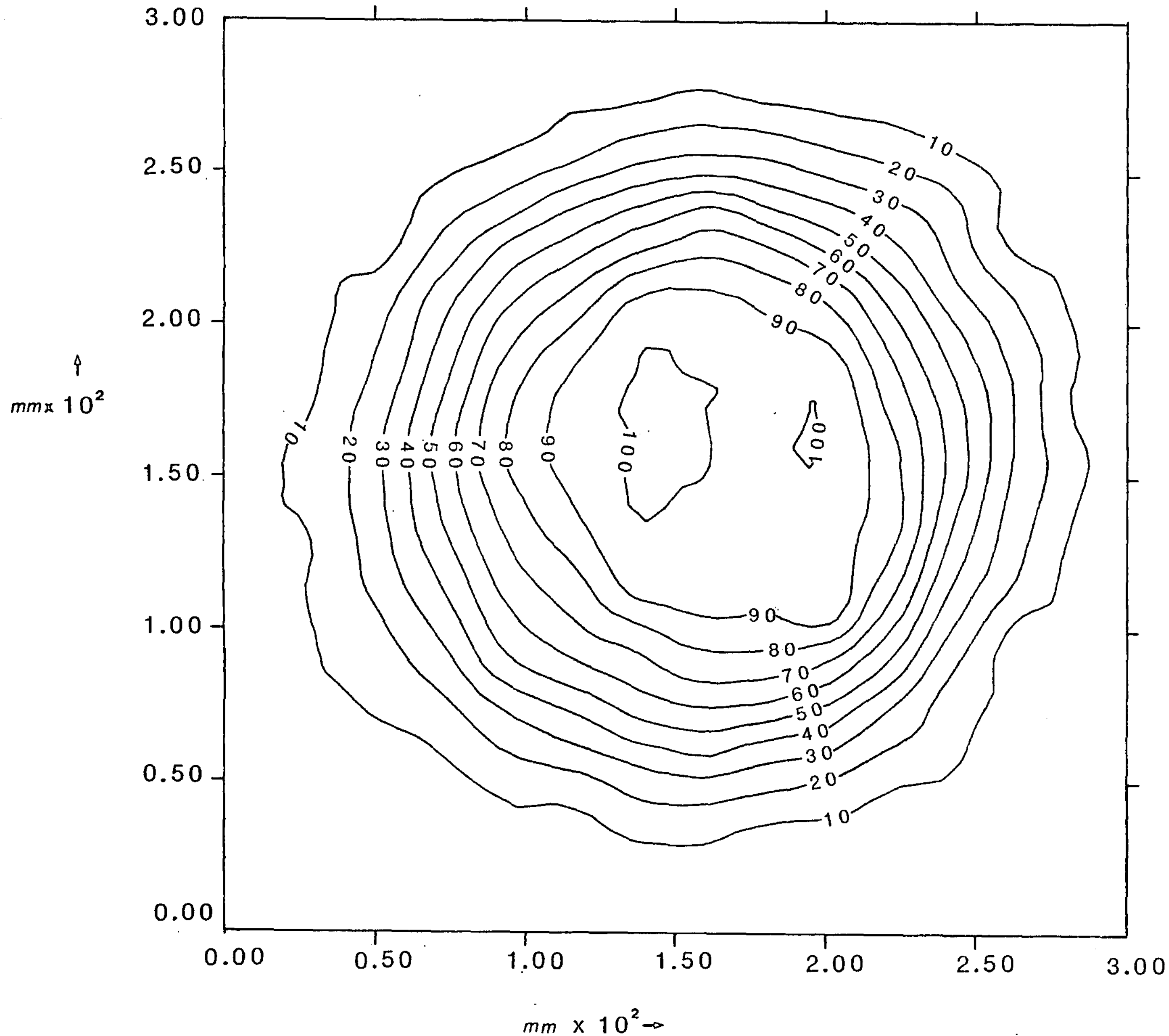


Figure 4.5 Relative response of MMR Mk II in field of view

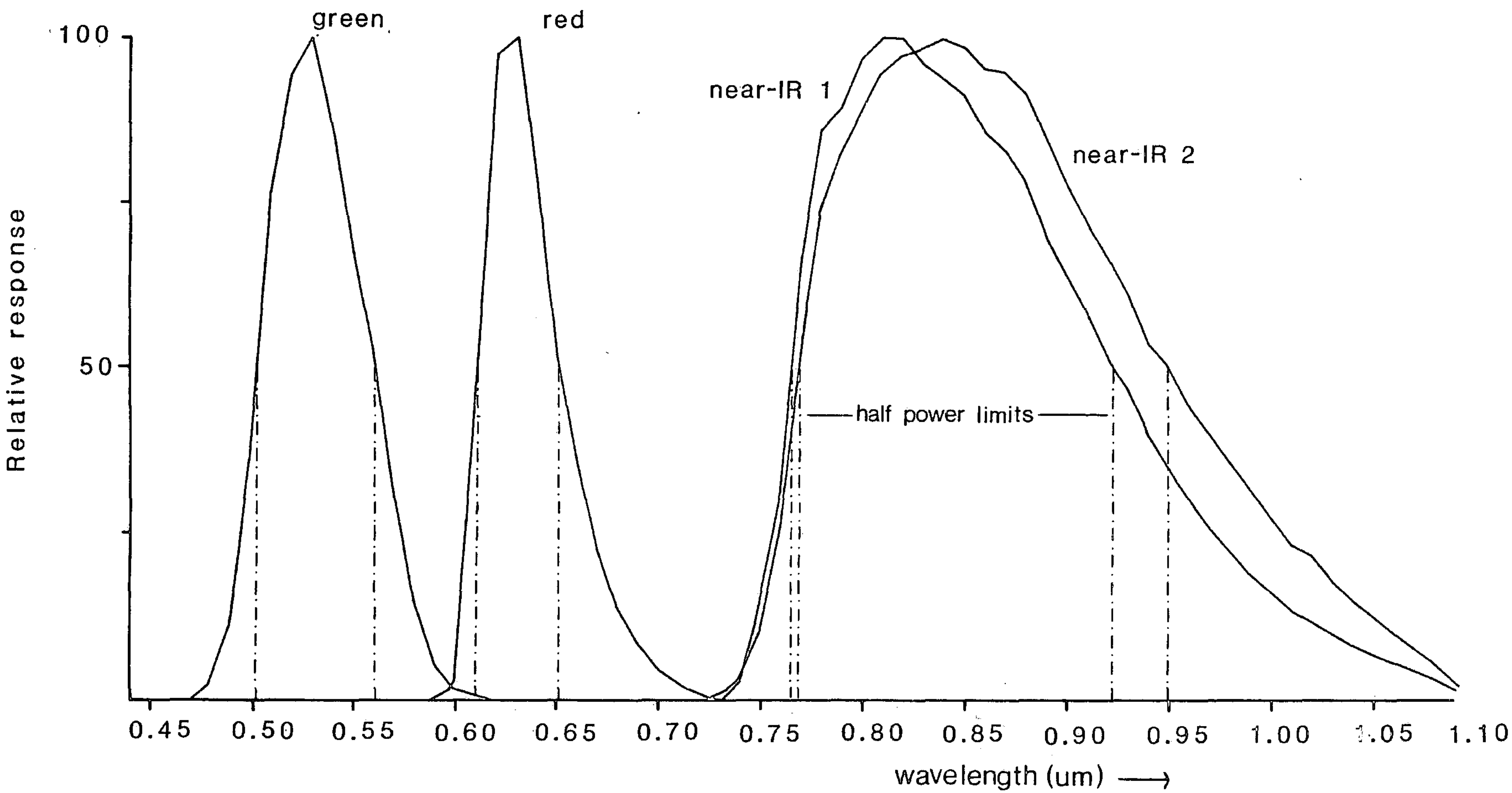


Figure 4.6a Spectral response MMR Mk I

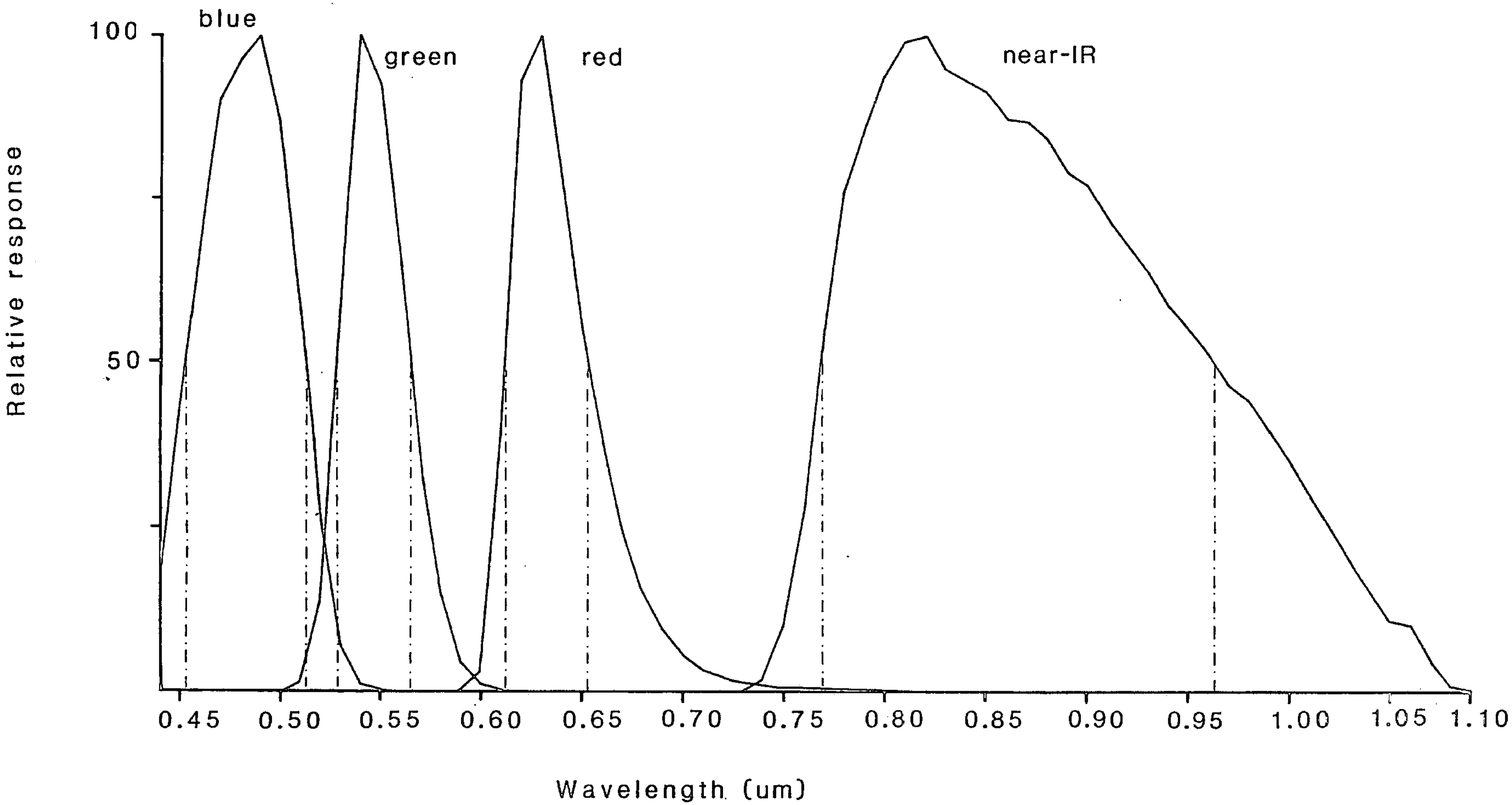


Figure 4.6b Spectral response, MMR Mk II

Data supplied by GeoData Unit, University of Southampton

Fluctuations in irradiation between sequential measurements of the target and the reference surface will introduce a certain amount of error to data collected in this way.

Duggin (1980, 1981a) suggests that two intercalibrated radiometers operating simultaneously, one measuring radiance from the target, the other recording direct and diffuse irradiance, are needed if such errors are to be avoided. Milton (1981) notes however that errors can still occur with the two radiometer method. If the sun's disk is obscured by passing cloud there will be change in the proportions of direct and diffuse radiation which will not be registered in the total measure of irradiance made by the second radiometer, and the radiance from the canopy will change in response to changes in proportion of shadow in the canopy. Milton therefore estimates that with irradiance changes of 10%, errors of 5% in the near-IR and 22% in the red wavelengths are still possible using the two instrument method. Duggin (1981b) cites his own experimental data to refute Milton's proposal and reasserts the superiority of the two radiometer approach. He concludes that radiance data obtained with one radiometer are not suitable for simulation studies but may be used in "less exacting" applications.

In practice the method adopted is largely decided by the availability of equipment and personnel. In this case the field equipment had to be carried and used rapidly by one person and only one radiometer was available at a time. The data were collected under clear skies to minimise errors due to change in irradiance. In an attempt to prolong the number of days when measurements could be taken the response of the grey card was observed continuously on a day of apparently uniform cloud cover. The readings fluctuated on a time scale considerably shorter than that needed to make sequential measurements of target and grey card. Data were therefore not collected under these conditions, although residual high frequency variation in irradiance will continue to affect measurements even on apparently clear days.

As noted in section 4.3, the radiance recorded from a vegetated target depends on the proportions of canopy components, soil and shadow visible to the sensor and can therefore vary considerably with the sensor view angle and the solar azimuth and zenith angles. The causes and effects of such angular dependence are reviewed comprehensively by Duggin (1985), Kimes (1983), Barnsley (1984, 1986) and Milton (1982). To minimise these effects the data were collected in the 4 - 5 hours spanning solar noon and at a constant azimuthal position to the sun and normal to the surface.

The error sources which affect ground radiometer measurements, namely unrecorded fluctuations in irradiance and discrepancies in the angular relationships of sun, sensor and target between sites, have therefore been minimised as far as possible in these data. The data are used here as a quick look exercise before a more detailed analysis of scanner data, not as a detailed simulation of the spectral response of moorland canopies. Residual inaccuracies caused by the method of data collection are therefore tolerable in the light of the exploratory nature of the survey.

4.5 Results of ground radiometer measurements

Following a pilot study in July 1983 ground radiometer data were collected in August 1983 with the MMR MkI and in May and August 1984 with the MMR MkII. The wavebands and the surfaces measured at each date are listed in table 4.3. Logistical problems of access to the moors in good weather conditions precluded the collection of further data.

4.5.1 Preliminary experiment - July 1983

A preliminary experiment was conducted to determine the number of sample points needed to characterise the response of each surface or canopy and estimate the number of surfaces that could reasonably be included in a regular measurement programme. The sedge dominated area was excluded from this experiment because access was not assured at the time of measurement. Fifteen sample points were located in each of 5 test sites by a random walk

	July 1983	August 1983	May 1984	August 1984
TEST SITES				
Exposed peat surface	*	*	*	*
Partially vegetated surface	*	*	*	*
Young heather	*			
Mature heather	*	*	*	*
Sedges/heather mix	*	*		
Sedges		*	*	*
New burn			*	*
WAVEBANDS				
Blue			*	*
Green	*	*	*	*
Red	*	*	*	*
Near-IR	*	*	*	*

Table 4.3 Test sites and wavebands used in ground radiometry programme. See text for full description of test sites and instrumentation.

		Green	Red	Near-IR 1	Near-IR 2
Exposed	$\bar{x}$	4.45	6.45	12.33	13.37
peat surface	c.v.	0.17	0.17	0.23	0.22
Partially vegetated	$\bar{x}$	4.06	4.68	24.35	25.58
surface	c.v.	0.10	0.18	0.29	0.30
Young heather	$\bar{x}$	2.26	2.30	18.94	19.53
	c.v.	0.07	0.05	0.13	0.14
Mature heather	$\bar{x}$	2.27	2.38	18.00	18.56
	c.v.	0.10	0.10	0.19	0.19
Sedges/heather	$\bar{x}$	3.20	3.29	21.02	21.69
mix	c.v.	0.26	0.26	0.23	0.23

Peat surface

	G	R	IR 1
R	.91		
IR 1	.89	.94	
IR 2	.89	.91	.98

Young heather

	G	R	IR 1
R	.69		
IR 1	.77	.70	
IR 2	.76	.69	.99

Sedges/heather mix

	G	R	IR 1
R	.98		
IR 1	.90	.81	
IR 2	.88	.80	1.00

Partially exposed surface

	G	R	IR 1
R	.87		
IR 1	-.17	-.54	
IR 2	-.16	-.53	1.00

Mature heather

	G	R	IR 1
R	.82		
IR 1	.90	.61	
IR 2	.88	.57	1.00

Table 4.4 Summary statistics and correlation matrices of reflectance for ground radiometer test sites, July 1983

procedure, translating sequences of random numbers into direction (compass bearing) and distance (number of paces).

The MMR Mk I radiometer was used to collect a set of three readings at each sample point and a final reading was calculated from these as described in section 4.4. No environmental information was recorded apart from a summmary description of the type and amount of cover. The spectral response of each surface is summarised in table 4.4 . Using the approach taken by Milton (1980) to calculate optimum sample size, figure 4.7 shows the cumulative means for each band. In the visible wavebands the means of the heather sites show the greatest uniformity and the peat surface has a surprisingly high variation given the nature of the surface. For all surfaces the mean is stable when nine or more sample points are included. On this basis nine or ten measurements would be considered sufficient to characterise the radiance of each of these surfaces in the visible wavebands. In the near-IR band, the radiance of sites 1 to 4 could be adequately characterised by a sample of ten or more points but the variation in the regenerating area would be shown accurately only by 12 or more samples. This method is however clearly sensitive to the order of introducing sites and has little statistical validity.

Curran and Williamson (1985) suggest a more rigorous method of determining sample size, using the approach of Rao and Ulaby (1977). This calculates the sample size required to estimate the validity of a characteristic from summary statistics of a pilot data set, i.e.

Sample Number (SN) = $(\sigma_s t / a)^2$

where σ_s is the standard deviation of the measured values

t is the Student's t value for n-1 degrees of freedom at 95%

a is the required degree of accuracy in units from the true population mean

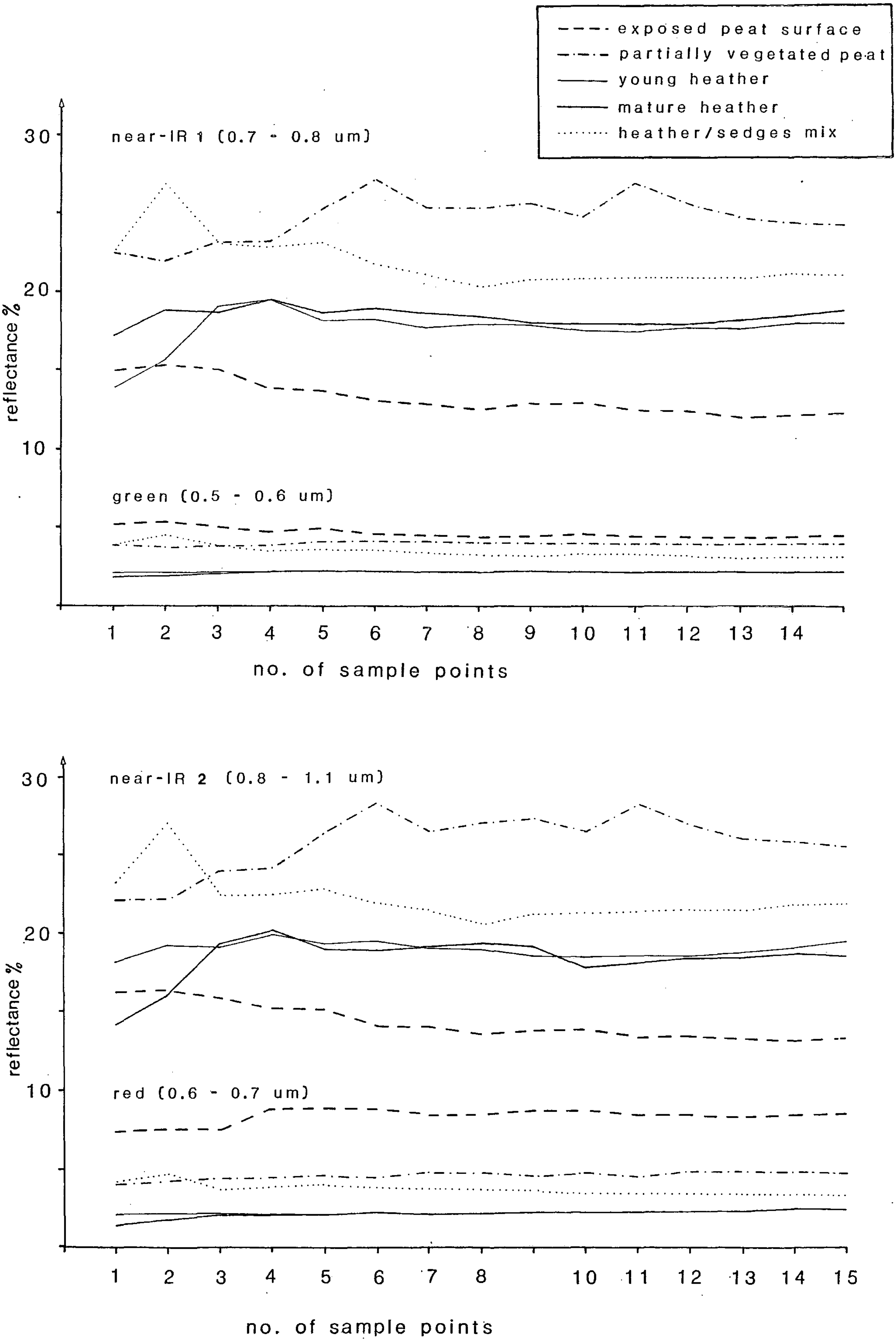


Figure 4.7 Cumulative mean reflectance values for radiometer sites, July 1983.

In practice the need to maintain a statistically viable sample size will work against the practical aim of collecting data from a number of surfaces in a short time period. This practical constraint meant that measurements at subsequent dates were made only at 12 sample points at each site. The associated accuracy of estimating the population mean, as calculated from the expression above, is given in table 4.4a This shows that the data set is undersampled at the mixed heather/sedges site in all bands, at the exposed peat surface in the visible bands and at the partly exposed surface in the near-IR.

The discussion of section 4.3 implies that the fully vegetated areas and the partially or fully exposed surfaces should be separated from each other by their spectral response, in parallel to the clear divisions made by clustering in the vegetation data. By this argument the exposed peat and the partially vegetated surfaces will also be separated from each other, the responses of the two heather classes will be largely similar, with a slightly higher variation in the mature class, and there will be overlap between the response of the heathers and that of the mixed Eriophorum/Calluna stand.

The graph of figure 4.8 confirms at least some of these expectations. There is a general division in the visible bands between the vegetated and the non-vegetated surfaces. The exposed peat and the partially vegetated surfaces overlap almost completely in the green band but are better separated in the red. This follows from chapter 2 and suggests that the red band is more sensitive to the presence of vegetation on otherwise exposed surfaces. Although some sites in the regenerating area are exposed peat, the remaining overlap between these two sites is most likely to be caused by the low spectral contrast of vegetation and substrate in these wavebands (section 4.3).

The two heather classes have a similar response in both the visible bands with little internal variation. The response of the mixed heather/sedges

	Green	Red	Near-IR 1	Near-IR 2
Peat surface	0.5	0.7	1.8	2.0
Partially exposed surface	0.3	0.6	4.6	4.7
Young heather	0.2	0.2	1.6	1.8
Mature heather	0.2	0.2	2.2	2.3
Sedges/heather mix	0.6	0.6	3.1	3.2

Table 4.4a Accuracy of estimate of population mean reflectance for radiometer data, 12 points in each site. See text for details. Entries are +/- refectance around mean.

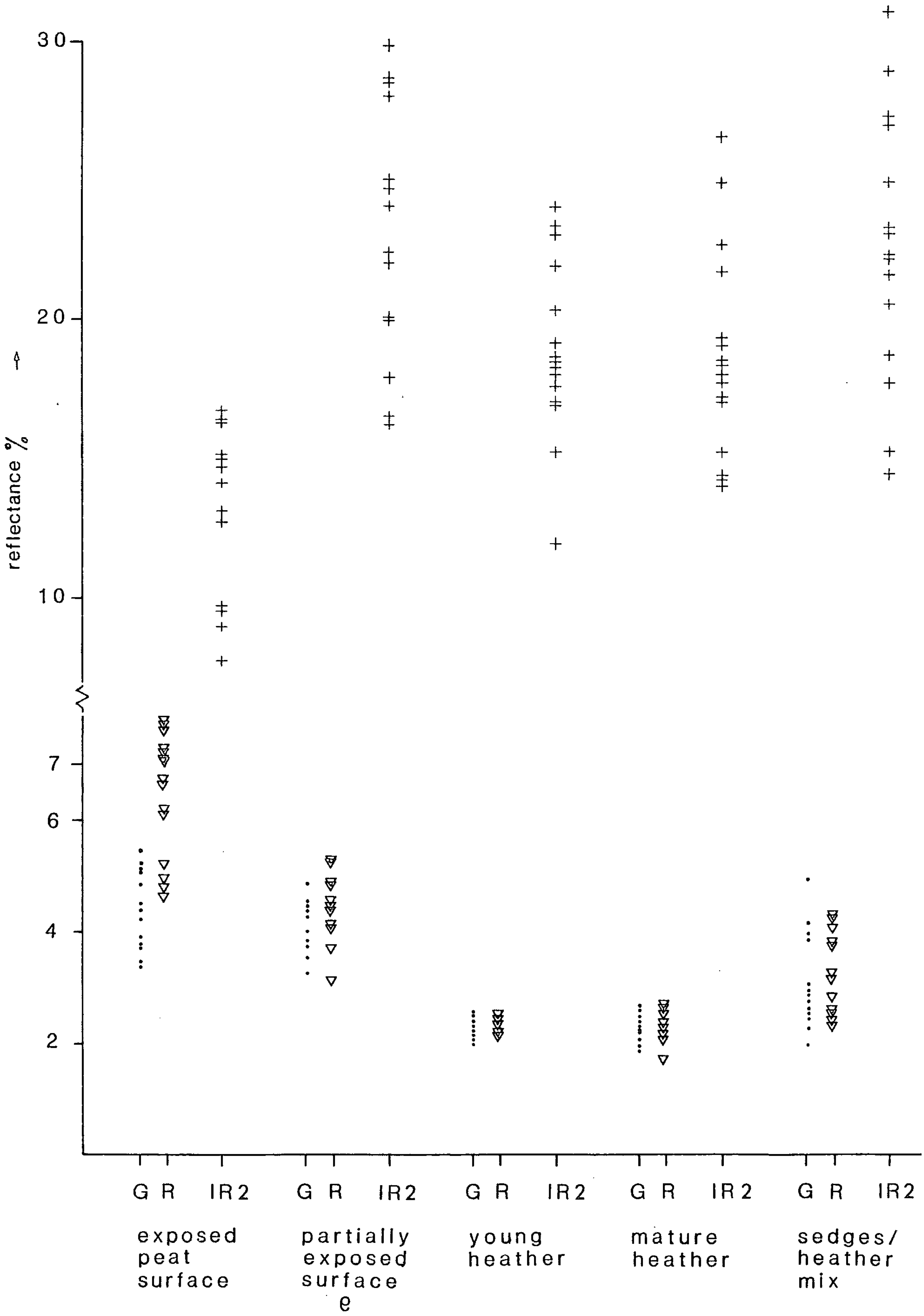


Figure 4.8 Summary graph: reflectance at radiometer test sites, July 1983

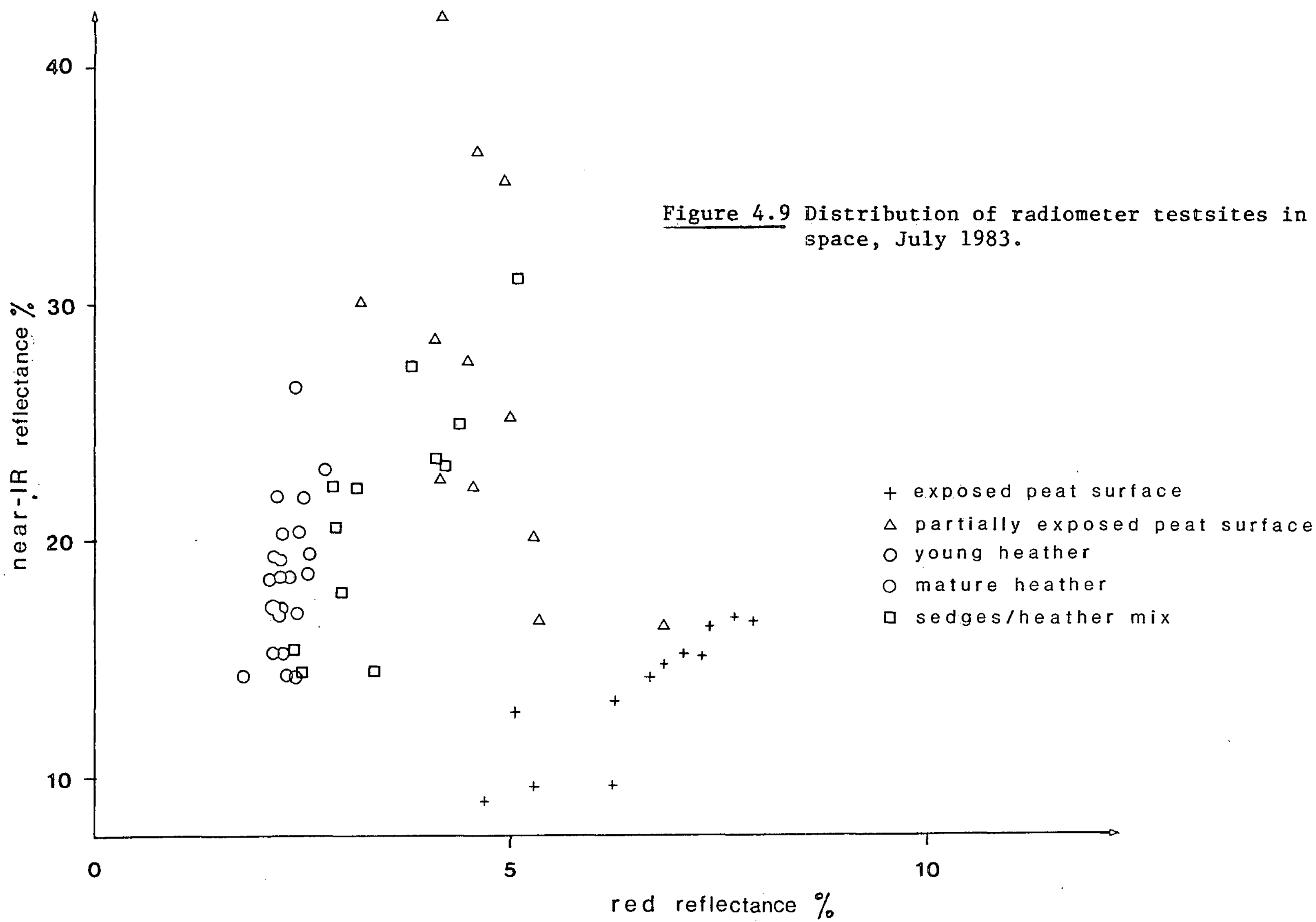


Figure 4.9 Distribution of radiometer testsites in red/near-IR feature space, July 1983.

stand is variable and overlaps that of the heather classes. It also shows some confusion with the exposed surfaces in this waveband.

In the near-IR bands the peat surface is separated almost completely from the vegetated and the partially vegetated surfaces. There is however almost complete correspondence between the near-IR response of the heather/sedges mix and that of the partially vegetated site. The two heather classes retain the relatively small variance found in the visible bands but their response is in the same range as the other vegetated sites. The overlap between the partially vegetated sites and those of full established cover is unexpected. It is possible that the dry crusted peats and the bleached heather stems present on the regenerating areas increase the background radiance at this site in the near-IR to the point where it mimics a high biomass.

Figure 4.9 shows that the information in the visible bands and the near-IR bands is complementary, in that the visible bands separate the established stands from each other and the near-IR wavelengths isolate the bare peat surface.

4.5.2 August 1983

A more detailed survey was undertaken in August 1983. The stand of sedges was substituted for the young heather canopy to increase the range of vegetation surfaces monitored. This had the practical advantage of bringing all the sites monitored onto one estate. The sites and sample points used are shown in figure 4.1 and table 4.3.

The 12 sample points at each site were located by a random walk procedure as in the July experiment. Each sample point was marked by a numbered peg so that repeat measurements could be taken at the same location.

At each sample point the following data were collected.

i. Three measurements in each of the 4 bands of MMR Mk I for the vegetation canopy directly adjacent and to the south of the marker peg.

ii. A colour transparency of this canopy, taken normal to the surface from a height of c.1m with a 35mm lens. The transparencies were used to calculate detailed information on the vegetation cover as described in section 4.2.1.

iii. Samples of litter and soil: moisture content and colour were determined in the laboratory as described in section 4.2.1.

The reflectance measurements are summarised in figure 4.10 and table 4.5. The single band plots for the August 1983 measurements are very similar to those for the July data.

The red and green wavebands have a similar pattern of response to each other in the August data although the response in the red band shows a higher variance at each site and the means are more clearly separated. These two features balance each other out so that the statistical separation between classes is similar for both wavebands, although the reservations (section 4.5.1) on the accuracy in representing variation at each site by 12 points still apply. The red band therefore has the greatest potential for detailed vegetation mapping in this environment as it separates the different communities but is also sensitive to the variations within them.

The spectral response of the Eriophorum is distinct from that of the heather stand in the visible bands but it covers most of the range of response of both the partially vegetated area and the exposed peat surface. This is clearly a potential source of error in the classification of canopies by their response in these bands, but the situation may be resolved in a spectral region, such as the mid-IR, which is more directly sensitive to the moisture content of the canopy and the substrate.

The main differences in response in the visible bands between the two dates is in the relative positions of the partly vegetated area and the exposed peat surface. Both sites have a more uniform response in the August data and the two are well separated. Part of this increased separation may be due to the rather drier conditions whereby the spectral contrast between the exposed surfaces and the vegetation is increased.

		Green	Red	Near-IR 1	Near-IR 2
Exposed peat surface	$\bar{x}$	4.90	6.99	15.13	15.97
	c.v.	0.09	0.08	0.78	0.12
Partially vegetated surface	$\bar{x}$	3.67	4.59	20.39	21.61
	c.v.	0.09	0.13	0.38	0.38
Mature heather	$\bar{x}$	2.38	2.57	25.20	26.67
	c.v.	0.09	0.13	0.38	0.38
Sedges/heather mix	$\bar{x}$	3.07	3.53	23.61	24.93
	c.v.	0.25	0.21	0.27	0.27
Sedges	$\bar{x}$	4.06	4.41	28.23	30.12
	c.v.	0.13	0.15	0.10	0.09

Peat surface

R	.95		
IR 1	.85	.78	
IR 2	.84	.77	.99
	G	R	IR 1

Mature heather

R	.70		
IR 1	.75	.16	
IR 2	.75	.14	1.00
	G	R	IR 1

Sedges

R	.89		
IR 1	.73	.56	
IR 2	.79	.60	.99
	G	R	IR 1

Partially exposed surface

R	.82		
IR 1	-.61	-.89	
IR 2	-.61	-.89	1.00
	G	R	IR 1

Sedges/heather mix

R	.97		
IR 1	.74	.64	
IR 2	.76	.67	1.00
	G	R	IR 1

Table 4.5 Summary statistics and correlation matrices of reflectance for ground radiometer test sites, August 1983.

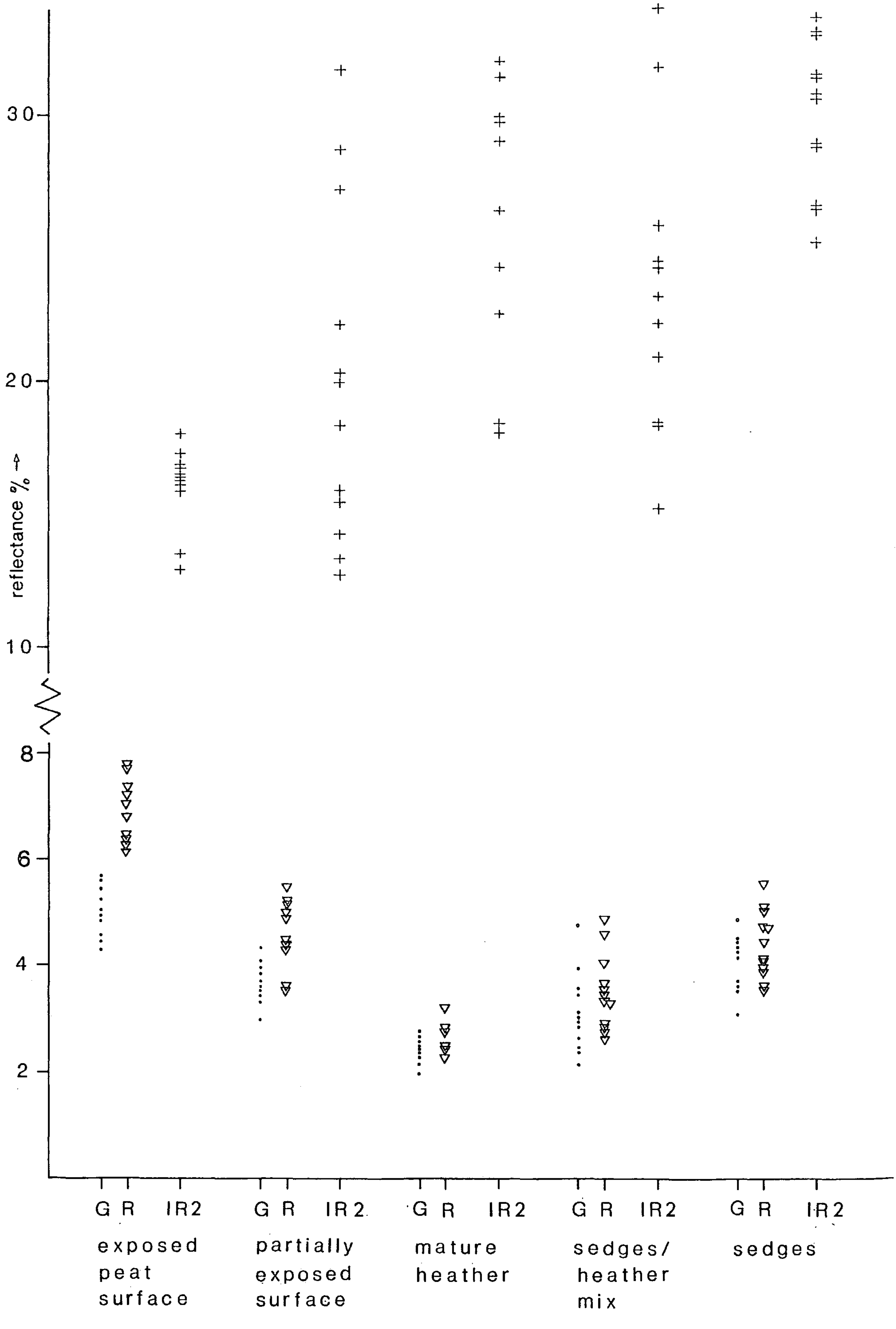


Figure 4.10 Summary graph: reflectance at radiometer test sites, August 1983

However this would also be expected to increase the variation within the regenerating site. There is therefore no clear source of variation which accounts for the greater uniformity in the August data. It is most likely that the higher variation in the July data is due to operator error. The August data are therefore considered to be a more reliable picture of the response at these sites.

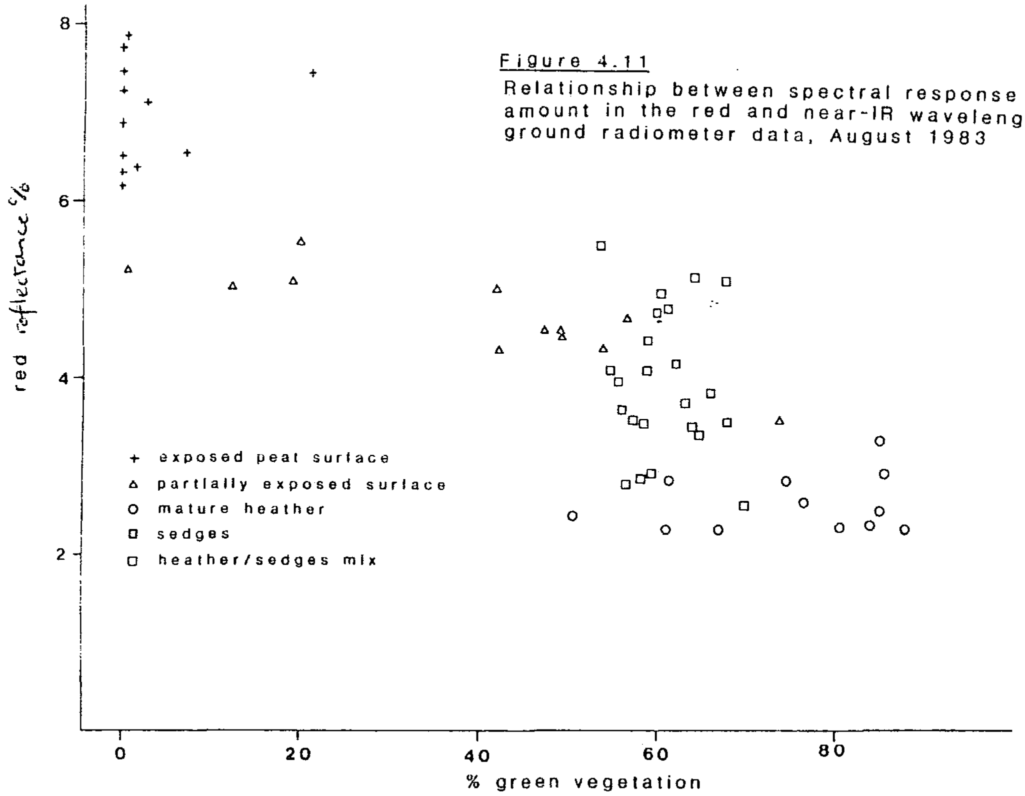
The clear separation of the peat surface, the partially vegetated area and the mature heather by their response in the visible wavebands parallels the separations made by the ecological descriptors of section 4.2. Similarly, the response of the mixed heather/sedges stand overlaps that of both the pure heather stand and the sedges in the two distributions.

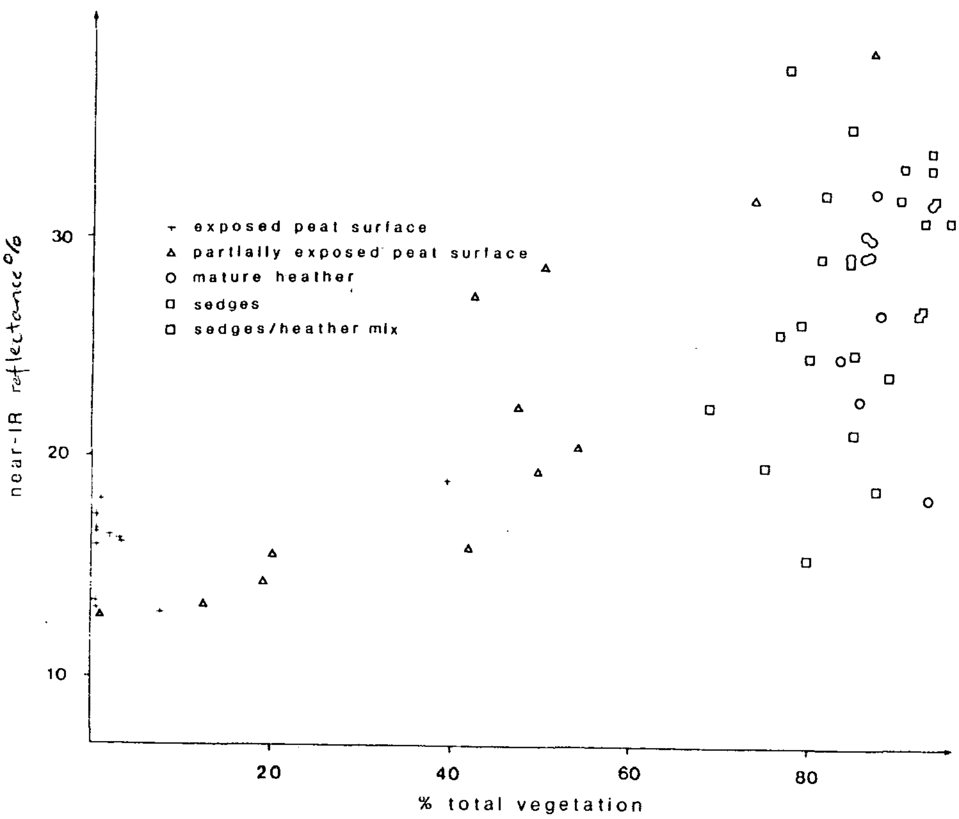
The results for the near-IR bands are similar to those for the July data. In the August data the response of the peat surface overlaps the extended range of the regenerating area. The lowest near-IR response in the regenerating sites comes from sample points which have low vegetation cover. The overlap is therefore a good parallel with the distribution of vegetation cover.

The amount and direction of overlap between the mature heather and the sedges stand are not as clear cut in the near-IR as in the visible bands. The Eriophorum site has a generally higher response than the heather but the two classes are not well separated. The response of the mixed site tends towards that of the mature heather. As in the visible wavebands the heather/sedge site has an identical range to the exposed peat and regenerating sites.

The response in both the visible bands at this date is most clearly related to the proportion of green vegetation at the sample point within the regenerating areas (figure 4.11a). The relationship persists in a reduced form in the Eriophorum canopy but is absent in the other vegetated stands. The near-IR reflectance is more clearly related to the total amount of vegetation present (figure 4.11b), although the relationship is different for each canopy and is not always consistent within a site. A

Figure 4.11
Relationship between spectral response and vegetation amount in the red and near-IR wavelengths, ground radiometer data, August 1983





better quantitative relationship was not expected between the vegetation descriptors and spectral response (see section 4.2).

As in the July readings the two visible bands are highly correlated (r >.70 for all sites), as are the two near-IR bands (r > .99 for all sites). The relationship between visible and near-IR bands ranges from strong positive correlation over the exposed peat surface to strong negative correlation over the partially vegetated area and these relationships are broadly consistent with those for the July data (table 4.4). The negative relationship between the visible and the near-IR response at the partially vegetated site is stronger in the August data and the positive relationship between the red band and the near-IR found at the heather site in July is absent in the August data.

In general however the four band data set reduces to two axes of variation, one in visible light and one in the near-IR wavelengths. The correlation matrices show that the two axes are not completely independent, but, as in the July data, they do contain complementary information (figure 4.12). The basic structure is as suggested by Richardson and Wiegand (1977). A perpendicular to the line formed by the response of the exposed surfaces is an approximate measure of the amount of vegetation present. As in the July data, the red waveband distinguishes between the established vegetation stands and the near-IR emphasises the distinction between the vegetated and the non-vegetated surfaces. Some overlap remains between the response of the two heterogenous classes - the regenerating areas and the Eriophorum/Calluna mix- and the other established canopies. Figure 4.12 therefore matches the outline of section 3.5 (in chapter 3) which suggests that clusters defined by the vegetation descriptors will have an approximate parallel in the spectral feature space although the relationships between the two sets of axes may not be direct.

The amount of spectral overlap between the more variable classes is due in part to the spatial resolution of the ground radiometer. In the mixed heather/sedge site the reflectance of each sample point in the visible and

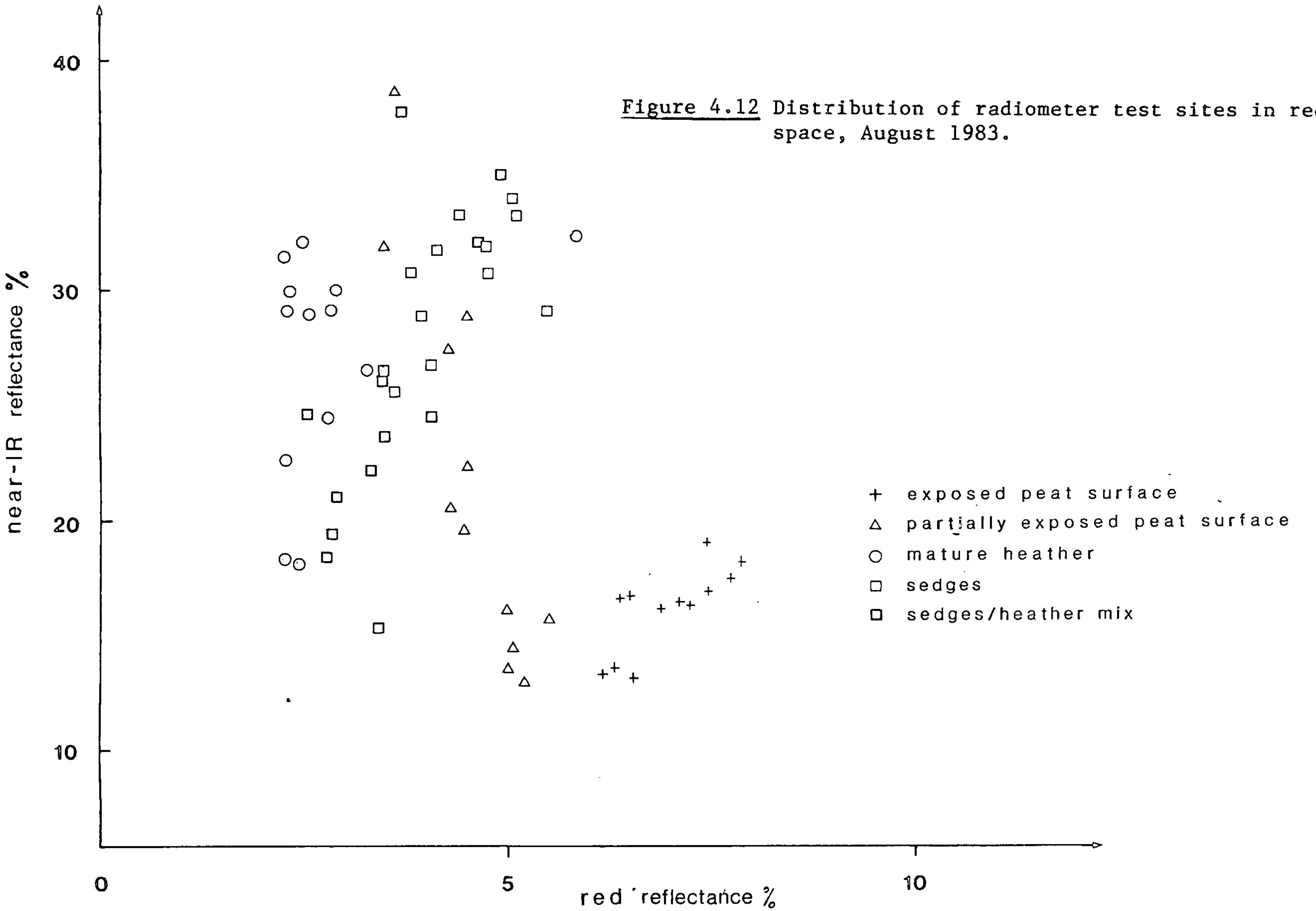


Figure 4.12 Distribution of radiometer test sites in red/near-IR feature space, August 1983.

the near-IR wavebands falls along a continuum between pure heather and pure Eriophorum, the position of each point depending on the proportions of each species present in the canopy. If the spatial resolution were decreased all sample points would contain elements of both species. Most points would therefore fall between the two extremes of reflectance to form a new discrete group, although complete separation from the pure stands is unlikely. Similarly an averaged reflectance for the regenerating areas would give a new grouping between the vegetated and the non-vegetated stands.

These variable sites could be identified in data of this spatial resolution by their textural characteristics, but their internal variability and spectral separation will be represented differently in data with a lower spatial resolution. Since any resolution is sub-optimal for some or all of the elements in a scene, this problem is likely to occur for some groups at all scales of interpretation. This is discussed in greater detail in later sections of the thesis.

In relation to the objectives set out in section 4.1, the July and August radiometer data have established the following:

i. Some of the critical ecological divisions in the moorland community can also be made in remotely sensed data.

ii. In broad terms the visible bands are sensitive to the type and amount of vegetation present, the near-IR bands are sensitive to the amount of vegetation present.

iii. The elements of the moorland community can be distinguished more clearly in multi-spectral data than in any single band at these wavelengths.

4.5.3 May and August 1984

Ground radiometer data were also collected in May and August 1984 with the MMR Mk II. The August data were used to check the stability of the relationships found in July and August of the previous year. The May data were examined primarily to indicate whether the reflectance of the test sites changes over the growing season, and therefore whether temporal resolution might be an important variable in monitoring the moorland community.

The MMR MkII includes a blue waveband, which, as described in chapter 2, is expected to hold broadly similar information to the red waveband. There is a slight difference between the response of the two radiometers in the green band (figure 4.9) but the relative response curves for the red and near-IR bands are almost identical. As far as possible the measurements were taken at the sample points used in the August 1983 survey. In all sites two or three sample points had been disturbed at each date and additional random points were taken to keep the total at twelve sample points per site. Both sets of August measurements were taken with similar preceding environmental conditions. No differences in reflectance were expected apart from those caused by the change of instruments.

The Calluna/Eriophorum site was burnt in the early spring of 1984. The "new burn" surface substituted for this class is a composite of measurements from this area and a neighbouring patch, previously over-age heather, burnt at the same time. No formal environmental information was collected for this class although brief observations were made on site.

The reflectance of the surfaces in August 1984 in the visible and near-IR bands are shown in figure 4.13 and summarised in table 4.6. The surfaces monitored in both August 1983 and August 1984 have a similar pattern of response at the two dates in the green waveband, apart from a slightly poorer discrimination of Calluna and Eriophorum in the 1984 data set. The new burn site is however grouped with the semi-vegetated site of regenerating heather in this band in the 1984 data, and has a partial overlap with the mature heather class. The effect of the dark charcoal surface is apparently to mimic the response of vegetation in this waveband.

		Blue	Green	Red	Near-IR
New burn	$\bar{x}$	3.84	5.08	5.79	10.42
	c.v.	0.18	0.13	0.15	0.16
Exposed peat surface	$\bar{x}$	5.77	7.37	9.25	19.83
	c.v.	0.21	0.07	0.07	0.07
Partially exposed surface	$\bar{x}$	3.65	5.63	5.94	23.45
	c.v.	0.15	0.08	0.08	0.36
Mature heather	$\bar{x}$	3.77	4.44	6.35	29.02
	c.v.	0.16	0.07	0.14	0.12
Sedges	$\bar{x}$	2.90	5.59	5.67	29.69
	c.v.	0.08	0.11	0.09	0.12

New burn

G	.95		
R	.98	.94	
IR	.48	.69	.54
	B	G	R

Partially exposed surface

G	-.14		
R	.81	-.37	
IR	-.86	.16	-.70
	B	G	R

Sedges

G	.71		
R	.64	.52	
IR	.44	.48	.66
	B	G	R

Peat surface

G	.87		
R	-.17	-.54	
IR	-.16	-.53	1.00
	B	G	R

Mature heather

R	.82		
R	.90	.61	
IR	.88	.57	1.00
	B	G	R

Table 4.6 Summary statistics and correlation matrices of reflectance for ground radiometer test sites, August 1984.

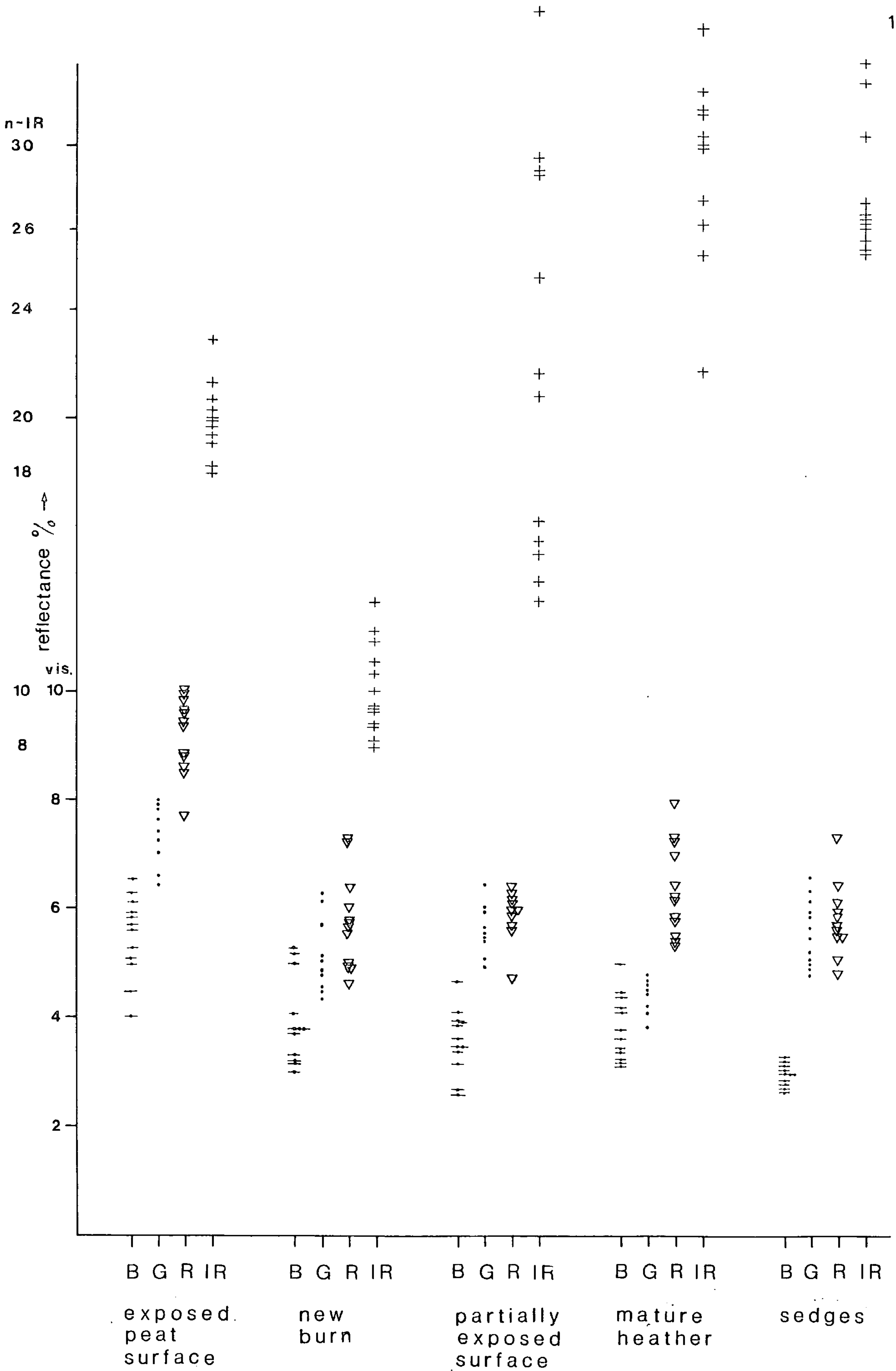


Figure 4.13 Summary graph: reflectance at radiome ter test sites, August 1984

The pattern of response in the red waveband is also similar at the two dates, apart from the response of the Calluna stand which is surprisingly high and variable in the 1984 data. This means that only the peat surface is isolated from all other sites in this band. The blue waveband contains very similar discriminatory information to the red wavelengths (figure 4.13) although the exposed peat surface is rather less clearly separated from all other sites. In addition the range of response from the Eriophorum stand is reduced in the blue wavebands and almost all measurements are lower than those of the heather stand.

Therefore, although the general pattern of response is the same across the three visible bands and they show high correlation at most sites (table 4.6), the similarities disguise minor variations in response which are important in isolating the test canopies.

The near-IR response of the test sites is similar to that in the August 1983 data. Some differences occur within the regenerating class as several new sample points had to be selected at this site.

The newly burnt surface is clearly separated from the exposed peat surface and all other vegetated areas in the near-IR band. This is an important result as it implies that the near-IR wavelengths could be used to map the extent and location of newly burnt sites over the moor and thereby monitor both the level of active management on the moor and locate the sites of accidental fires.

Figure 4.14 shows that the basic two-dimensional structure of the feature space is maintained in the 1984 data. The major difference between the feature space of the two August acquisitions is in the positioning of the heather class in the red band. The exposed peat surface is more clearly separated from the vegetated areas in the 1984 data but otherwise there is little difference between the two distributions.

In contrast, there is high inter-band correlation across all wavebands in the May data (table 4.7) and the shape of the visible:near-IR feature space

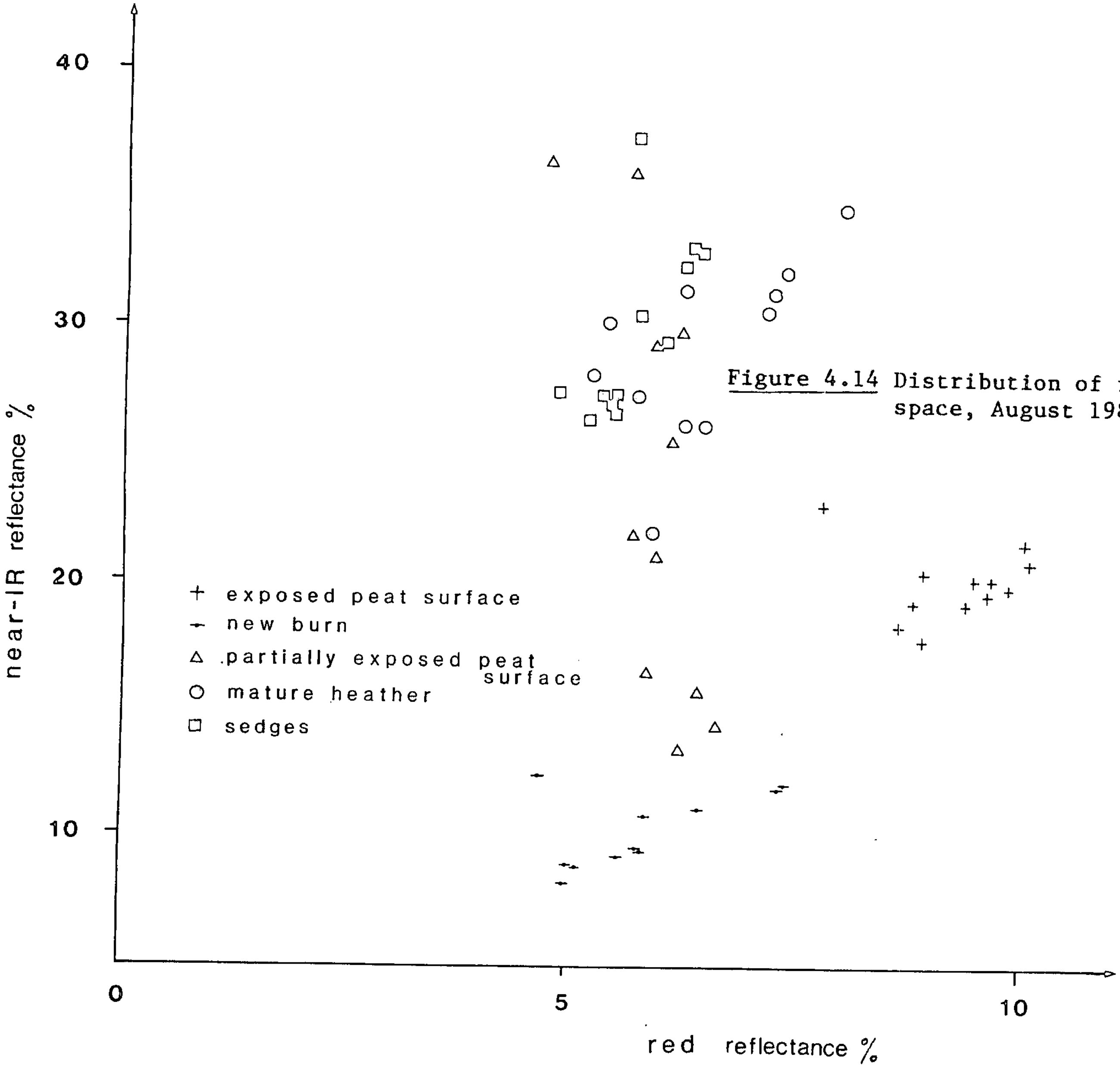


Figure 4.14 Distribution of radiometer test sites in red/near-IR feature space, August 1984.

		Blue	Green	Red	Near-IR
New burn	$\bar{x}$	2.20	2.78	3.60	6.70
	c.v.	0.12	0.16	0.17	0.26
Exposed peat surface	$\bar{x}$	4.55	5.65	8.02	16.44
	c.v.	0.08	0.08	0.06	0.09
Partially exposed surface	$\bar{x}$	3.52	5.21	6.60	17.84
	c.v.	0.18	0.19	0.21	0.18
Mature heather	$\bar{x}$	1.25	2.09	2.47	11.80
	c.v.	0.08	0.04	0.07	0.12
Sedges	$\bar{x}$	3.06	4.36	5.79	14.38
	c.v.	0.24	0.23	0.20	0.16

New burn

	B	G	R
G	.87		
R	.94	.85	
IR	.72	.56	.71

Mature heather

	B	G	R
G	.91		
R	.85	.95	
IR	.78	.89	.97

Partially exposed surface

	B	G	R
G	.91		
R	.85	.95	
IR	.78	.89	.97

Peat surface

	B	G	R
G	.26		
R	.71	.46	
IR	-.65	.04	-.24

Sedges

	B	G	R
G	.81		
R	.65	.37	
IR	-.58	-.42	.12

Table 4.7 Summary statistics and correlation matrices of reflectance for ground radiometer test sites, May 1984.

is substantially different from that of both the August data sets (figure 4.15). In particular the fully vegetated sites are not so clearly separated from the exposed and partially exposed sites in the near-IR band. With the exception of the regenerating site however the test sites are isolated from each other.

A low visible reflectance is expected in the vegetated stands at this time as it is a period of maximum productivity in the heather (Gimingham, 1960). In the red and the blue bands the mature heather stand returns to the lower reflectance found in the August 1983 measurements. The slight differences in response between the visible bands found in the August 1984 data are also present in the May data. In particular, the response of the charcoal surface on the newly burnt site is similar to that of the heather canopy in both the green and the red wavebands but is largely separated from it in the blue band. The red band distinguishes the new burn more clearly from the regenerating and Eriophorum stands. The spring burn was carried out only a few weeks prior to these measurements and the newly exposed surface is clearly differentiated from all other exposed surfaces.

Compared to the August data each test site has a much more variable response in the near-IR band. The vegetated sites are separated from the new burn but not from the exposed or the partially exposed surface. The differences found between the response of the moorland sites in the May and the August data are not discussed further here, but are sufficient to be explored more fully in airborne scanner data, reported in chapter 6.

4.6 Summary

The radiometer data were collected and examined to test the validity of the proposal that vegetation types which group together on environmental variables will also group together when defined by their spectral response.

The small range of wavelengths measured and the inaccuracies inherent to the data clearly preclude any rigorous extrapolation from the radiometer data to the results expected from satellite sensors (and see Duggin, 1985

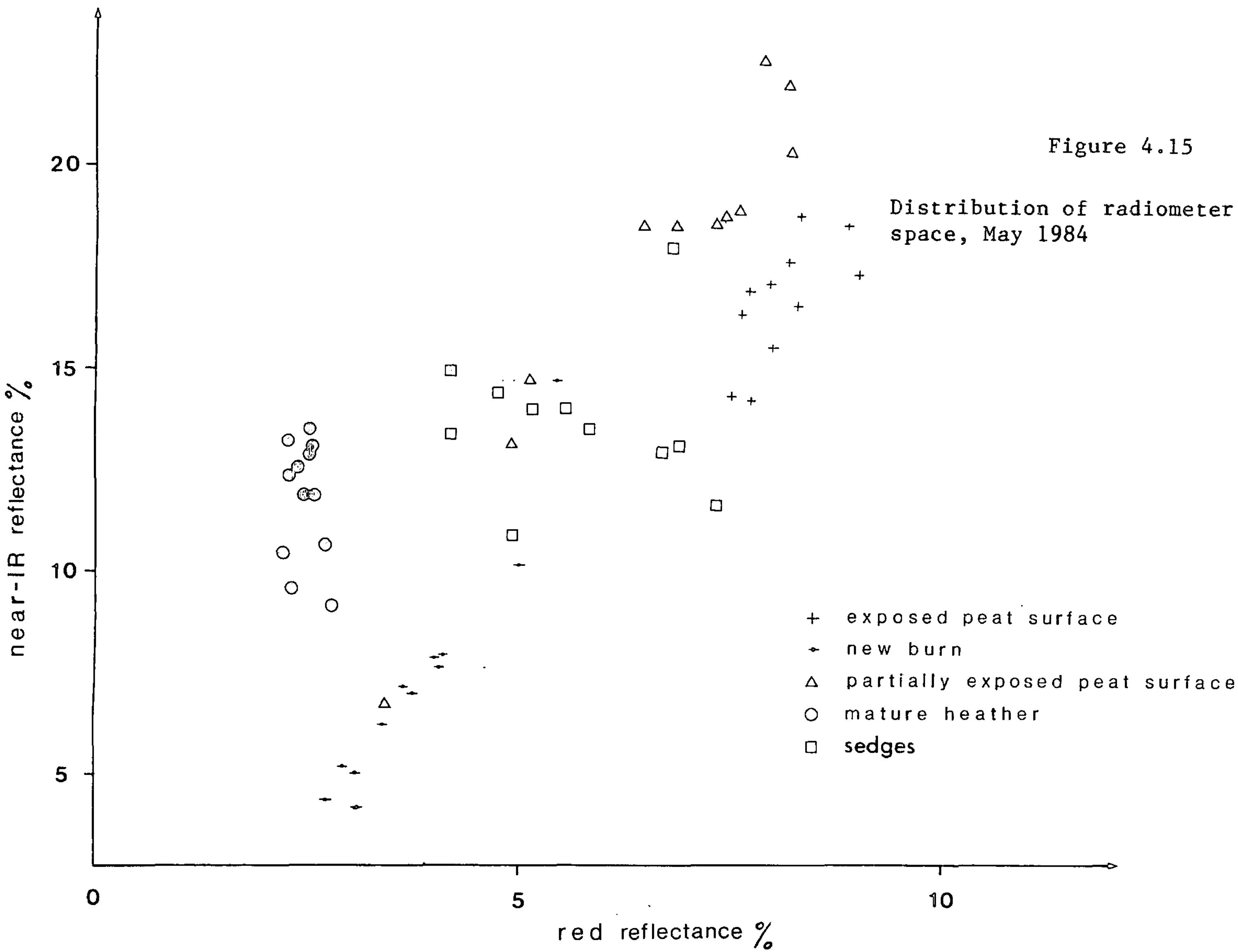


Figure 4.15

Distribution of radiometer test sites in red/near-IR feature space, May 1984 for further technical problems). However the results in section 4.5 show that, in general, sample points within a single vegetation type have reflectance values in the visible:near-IR feature space which are similar to those of other points within the same cover type. The importance of a multi-spectral approach has been recognised and further spectral information is expected to improve both the internal cohesion of the more variable clusters and their separation from all other clusters.

The spatial resolution of the sensor relative to the periodicity of the target may be an important parameter in determining the spectral separation of these communities. The differences in response between the May and the August readings demonstrates that temporal resolution may also be critical.

Given the error terms calculated in section 4.5.1., the results from this limited data set therefore confirm the idea that moorland vegetation types can be separated and identified by their spectral response. A more detailed analysis of the data from airborne and space systems is therefore justified. In addition the parameters of spectral, spatial and temporal resolution are seen to interact and affect the probability of correctly identifying a sample point even at this simple level. The following chapters examine the importance of these resolution parameters in greater detail.

Chapter Five: Detailed analysis of multi-spectral scanner data, the importance of spectral resolution

5.1 Introduction

This chapter builds on the results of chapter four by examining the hypothesis that multispectral remote sensing data give a better separation and identification of moorland targets than do single band data of any spectral region. As outlined in chapters 2 and 4 the effect is expected to be greatest where the response in each waveband is uncorrelated to that in the other bands and the feature space is multi-dimensional. The discriminatory information in an image should therefore increase in proportion to the number of independent wavebands or spectral regions available.

In most natural and semi-natural communities however the distribution and separation of the component cover types can be described by a limited number of ecological variables, which are measured more or less directly by different spectral regions, as discussed in chapters 2 and 4. In this case some wavelengths will clearly be more successful than others at isolating the target canopies and the addition of further independent wavebands may not increase their separation.

Therefore, although any combination of wavebands or spectral regions may increase the total amount of discriminatory information in an image, particular combinations will provide more useful separations for specific sets of targets. The general hypothesis is therefore refined to the statement that a set of targets will be best separated by a combination of wavebands peculiar in number and identity to that set or subset of targets. The wavebands within this combination will most often be uncorrelated.

Testing this hypothesis will decide whether, for this environment, the discriminatory information in the data set can be retained in a reduced set of wavebands which is common to all vegetation types. In practical terms this will determine whether time and money can be saved in the analysis of the data. In broader terms it will determine the importance of the spectral content of remotely sensed data for moorland management and therefore the spectral resolution of earth resources satellite sensors. This is particularly important as the move towards imaging spectrometry implies that the spectral dimension in satellite sensor data should be increased at the expense of other resolution parameters which may be more desirable in this environment.

Section 5.2 describes the data analysed in this chapter and the test site over which they were collected. Section 5.3 describes the methodology and the statistical measures used in this chapter. Section 5.4 uses simple measures of univariate separation to describe the ability of each of the seven ATM wavebands to separate test sites drawn from the important moorland canopies identified in chapter 3. The number of independent dimensions in the data is examined through correlation matrices and principal components analysis in section 5.5. The Transformed Divergence (TD), described in section 5.2, is used to measure the spectral separation of all pairs of test sites in all combinations of two to seven wavebands. This analysis defines the size and composition of the subsets of wavebands which give the optimal separation between important pairs and groups of sites. The results of this analysis are discussed in section 5.6.

Section 5.7 evaluates the original hypotheses and discusses the importance of spectral resolution as a characteristic of remotely sensed data in this environment. The implications of these results for a GIS approach to data selection and moorland management are assessed in the concluding chapter (chapter 8), together with the results of chapters 6 and 7. Alternative forms of analysis and extensions to this work are also discussed in the final chapter.

5.2 Data and test site.

The data used in this chapter were acquired with the Daedalus AADS1268 scanner in September 1983, under the Natural Environment Research Council (NERC) "MSS '83" aircraft campaign (Williams, 1984). A technical description of the the Daedalus scanner is given in chapter 2.

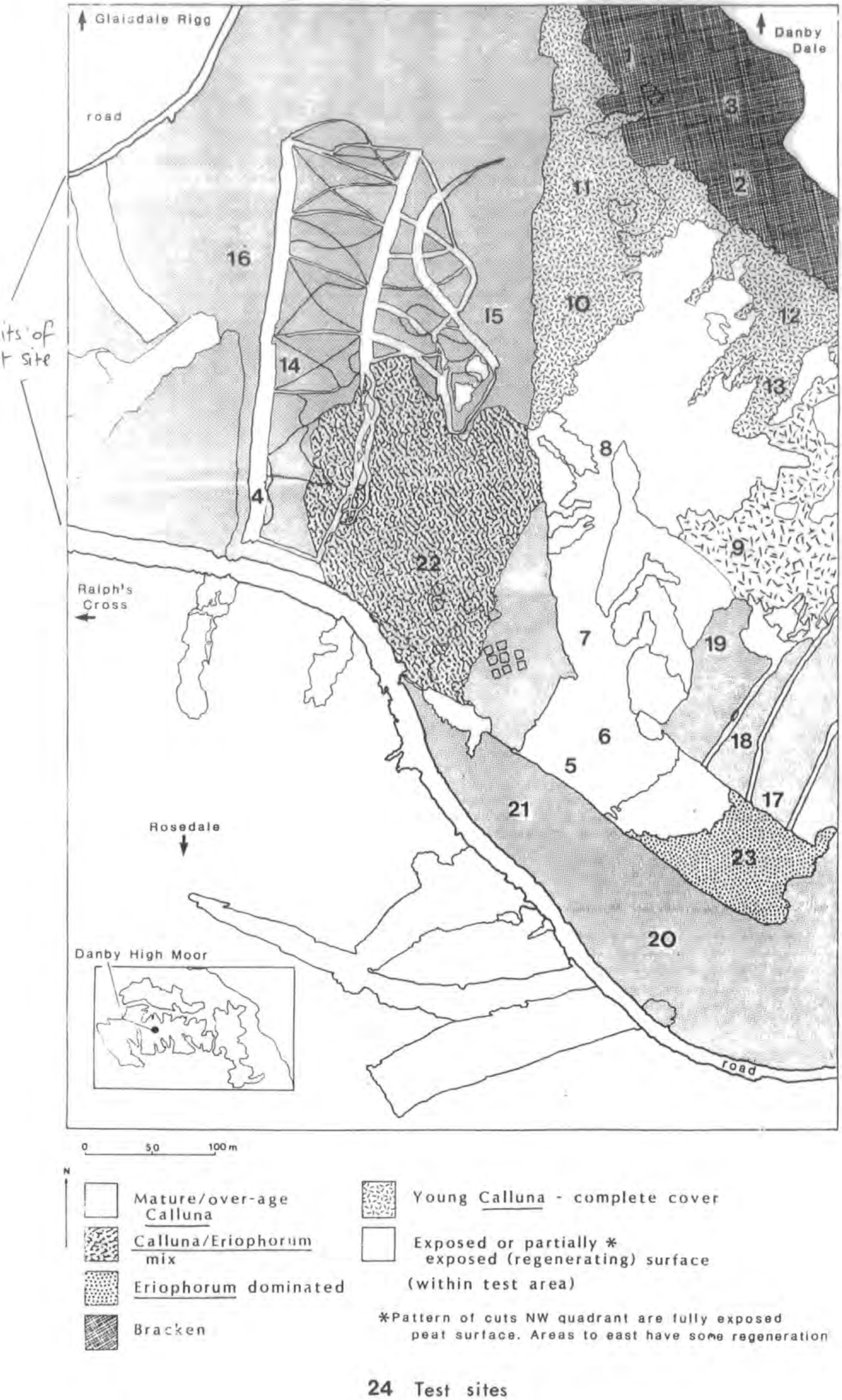
The pixel size in the scanner data, 1.4m x 1.3m, is similar to the IFOV of the ground radiometer and is approximately the size of the largest patches of regenerating vegetation in the partially exposed areas. This is the smallest scale of variation in the moorland vegetation which is normally of importance to management. The ATM data and the ground radiometer data are therefore expected to show a similar and relatively high variance in response at each site, particularly at the partially exposed surfaces, which will be largely averaged out in the satellite TM data. If this high within class variation has an effect on the spectral separation of targets the results from the ATM data, given the discrepancies between airborne and satellite data oulined in chapter 2, will be an underestimate of the discriminating ability of satellite TM data. The use of resampling and smoothing routines to bring the ATM data to the spatial resolution of the TM data was not pursued.

The test site is centred on the ground radiometer site at Danby High Moor. It includes virtually all of the important cover types within a small area and the pattern of road junctions and cuts in the heather is easily recognisable in all the imagery acquired during this work. Figure 5.1 is a schematic map of the vegetation at the test site, based on figure 4.1 of chapter 4. A brief description of the training sets, which are typical examples of the cover types described in chapters 3 and 4, is given in table 5.1 and their position is marked on figure 5.1. A foldout list of the test sites is available in Appendix 2 for use with subsequent tables and figures in the thesis. Initial investigations of the data used duplicate and triplicate test sites and covered most of the area shown in figure 5.1. Those where the spectral characteristics are close or

Site number	Description
1 - 3	Dense bracken stands
4	Peaty podsol surface, exposed by cutting and clearing heather. Very little vegetation.
5 - 8	Partially vegetated surfaces, regenerating after fire. Numbering of sites corresponds to increasing proportion of vegetation cover. The dominant vegetation is Calluna (up to 12 cm high), although Vaccinium and grasses are present. There are a large number of dead heather stems, and, where exposed, the peat has a surface crust which is light in colour.
9 - 13	Areas with complete or virtually complete cover of vigorous young heather, forming a carpet c. 15 cm high.
14 - 16	Mature heather stand, compact growth with complete canopy. Approx. 22cm in height.
17 - 21	Over-age heathers: 17 - 19: advanced stage of sites 14-16, uneven canopy 20 - 21: older stands, uneven gappy canopy.
22	Mixed mature/over-age Calluna and Eriophorum
23	Eriophorum dominated area, Calluna under-storey

Table 5.1 Description of test sites, Danby High Moor. Ground radiometer sites - 4, 5, 14, 22, 23.

Figure 5.1 Distribution of vegetation at test area, Danby High Moor, and location of sample sites.



identical to those of their prototypes have been omitted from further analysis. Unless otherwise stated, tables of summary and separation statistics contain all remaining sites although the site numbering reflects the original sampling.

5.3 Methodology.

This chapter examines the spectral separation of common moorland canopies to determine the importance of each of the ATM wavebands which approximate the 7 Landsat TM bands for mapping and monitoring the moorland environment. This section gives a brief rationale for this approach and outlines the descriptive statistics used.

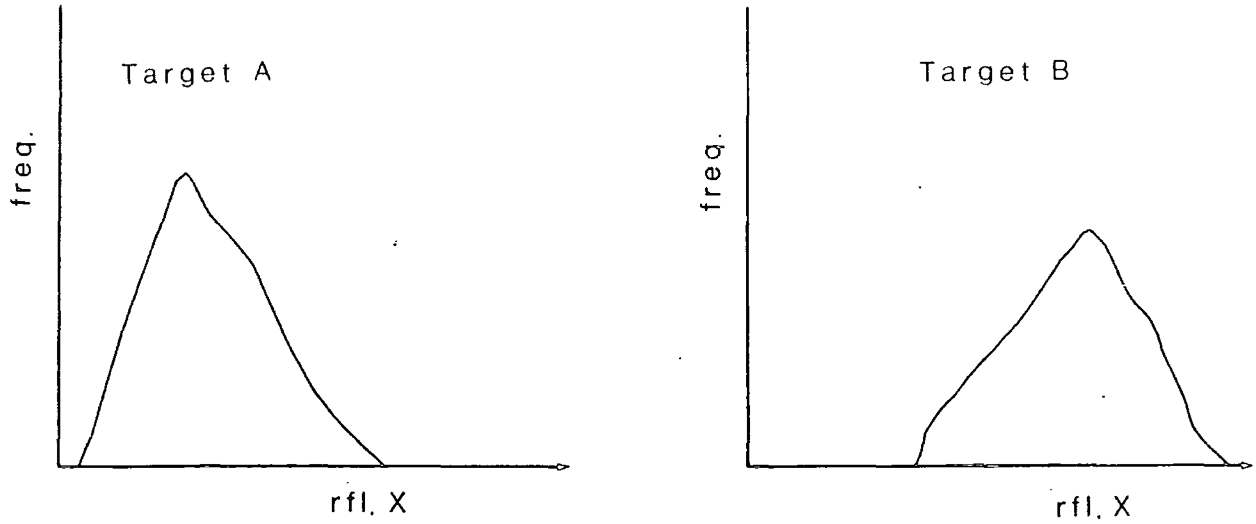
The analysis of remotely sensed data aims to recognise groupings within the spectral feature space and identify their ground properties. A new point or area is assigned to a spectral group or class and is taken to have the ground properties of that class. In a probabilistic classification a point, or a vector of radiance measurements, is assigned to the class to which, on the basis of its spectral characteristics, it has the highest probability of belonging. This probability is expressed as the weighted distance between the vector and the class standard in each dimension.

The probability of error in the classification is the probability that a measurement vector will be classified as one class when it is in fact an element of a different class or falls outside the boundaries of all defined classes. In the case shown in figure 5.2 there are two sources of error in the classification.

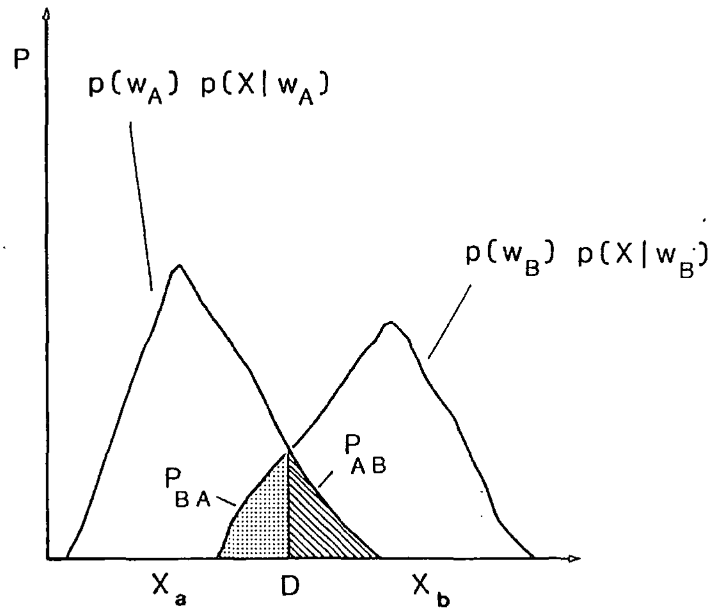
i. P_{AB} An element of A is wrongly classified as B

ii. P_{BA} An element of B is wrongly classified as A

and the overall probability of error is the sum of these two components, i.e.



a Response of targets A and B in waveband X



b. Probability density functions for classes A and B, assuming equal prior probabilities

Figure 5.2 Description of P_ϵ (probability of error in classification. P_ϵ is the sum of two error terms, P_{AB} and P_{BA}, which correspond to the hatched areas in the overlap of the two density functions. See text for explanation. After Swain and Davis (1978).

$P_E = P_{AB} + P_{BA}$

P_{AB} and P_{BA} correspond to the hatched areas in the area of overlap of the two density functions. Thus P can be written

$$P_E = \int_{X_a} p(w_B)\ P(X|w_B)\,dx + \int_{X_b} p(w_A)\ p(X|w_A)\ dx$$

The greater the area of overlap, i.e., the greater the similarity between the two classes, the higher is the probability of error in the classification of an unknown pixel. The results of a probabilistic classification therefore depend on the spacing or separability of the class standards in the spectral feature space.

This chapter examines P_E in the classification of selected targets in different combinations of wavebands. P_E can be measured directly by conventional accuracy assessments following classification. The integral expression in the definition of P_E cannot be evaluated analytically (Swain and Davis, 1978) and repeated classification was not possible with the equipment available. Statistics which measure the spectral separation of distributions were therefore used as surrogates. These are the Normalised Difference in the univariate case and Transformed Divergence for multiple band sets.

These measures will give a reasonable indication of classification accuracy where the target classes have a homogeneous response. Where the response is more variable, as a result of spatial variability in the vegetation which is greater than the resolution cell, as for example in the areas of mixed heather and sedges or the partially exposed peat surfaces, per-pixel classifications and therefore their statistical surrogates are less useful. In these cases a class will be recognisable in the imagery by the spatial frequency of differently classified pixels. The relative utility of automated classifications and visual interpretation of these data, or a combination of the two, has been examined by Milton et al. (1986) and is a topic for further study.

The Normalised Difference (Swain and Davis, 1978) is defined as

$$Dnorm = \frac{u_i - u_j}{\sigma_i + \sigma_j}$$

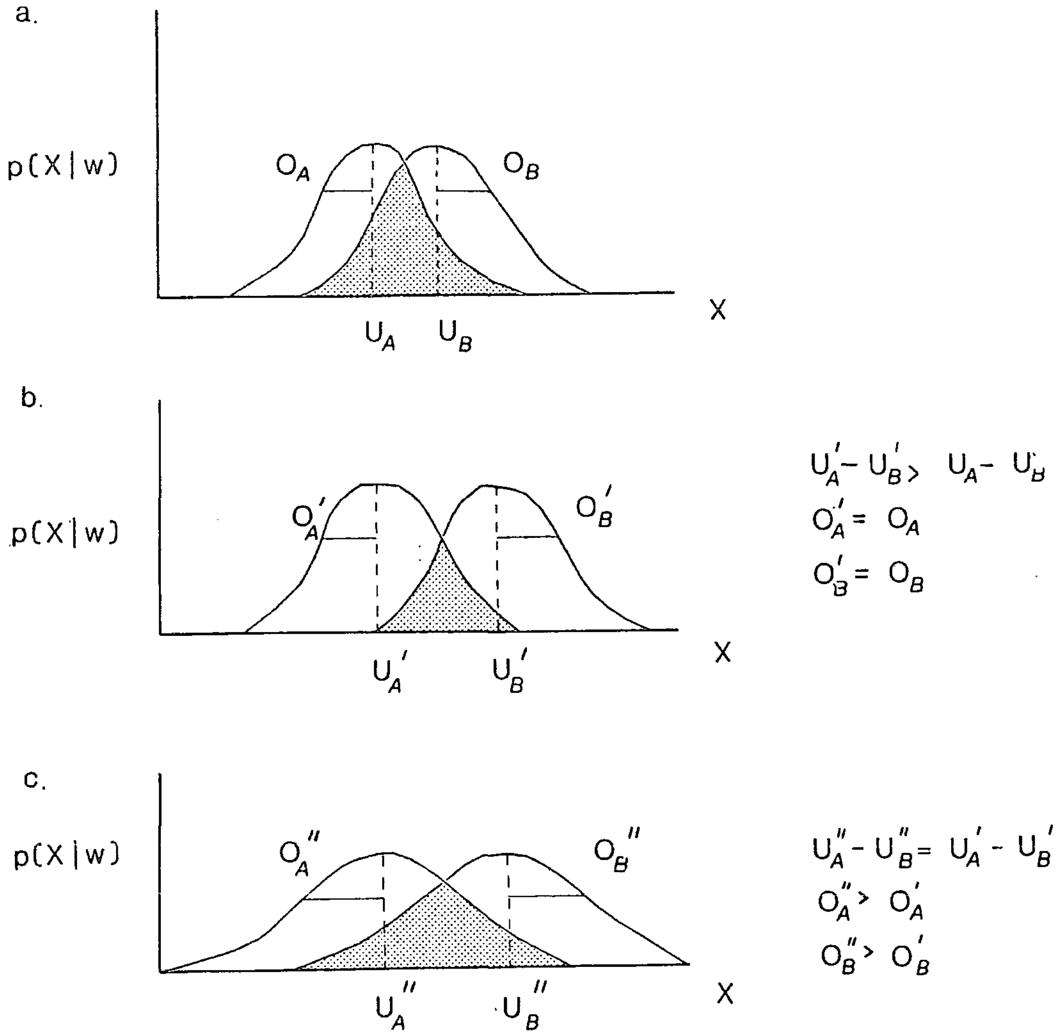
where u_i is the mean of distribution i, and σ_i is the standard deviation of distribution i on this variable. In remote sensing terms Dnorm measures the separation between two classes in a single waveband. Figure 5.3 shows why the standardisation is needed and also demonstrates the main drawback of Dnorm, that the separation between any two distributions with equal means is zero although they may have different variances. However, Dnorm is a convenient and practical way of summarising the statistical separation between two density functions for a single variable.

Dnorm is used in section 5.4 to determine whether there is any difference in the order and the magnitude of separation of sites between the 7 ATM bands. If so it is possible that the use of multi-spectral data can improve the discrimination of the targets and the general hypothesis, that multi-spectral data give a better separation and identification of moorland targets than do single band data of any spectral region, cannot be refuted at this stage.

The Transformed Divergence (TD) is used to measure the statistical separation of the training sets in a multi-dimensional feature space. TD is derived from the likelihood ratio L_{ij} for two classes i and j where

$$L_{ij}(X) = \frac{p(X|w_i)}{p(X|w_j)}$$

Figure 5.4 shows the definition of this expression and its relationship to



a. Original overlapping density functions

b. Increased separation of means decreases P_E

c. Increased variance increases P_E

Two distributions with equal means have zero separation, although their distributions are different

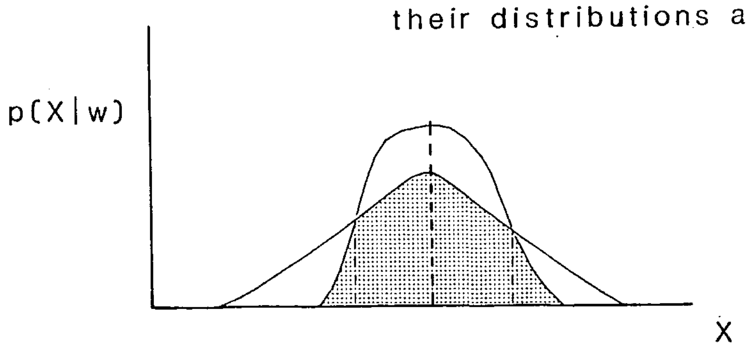


Figure 5.3 Properties of Dnorm (Normalised Difference) as a measure of P_E. After Swain and Davis (1978).

P_ε. If the log of both sides is taken, the expression becomes

$$L'_{ij}(X) = \log_e L_{ij}(X)$$

$$= \log_e p(X|w_i) - \log p(X|w_j)$$

Divergence is defined in terms of this log-likelihood ratio

$$D_{ij} = E\left[L'_{ij}(X)\,|\,w_i\right] + E\left[L'_{ji}(X)\,|\,w_j\right]$$

where E [] is the expected or average, i.e.,

$$E\left[L'_{ij}(X)\,|\,w_i\right] = \int_X L'_{ij}(x)\; p(X|w_i)\; dx$$

$$E\left[L'_{ji}(X)\;w_j\right] = \int_X L'_{ji}(X)\; p(X|w_j)\; dx$$

and the integrals are taken over the whole measurement space.

The divergence between two classes i and j is therefore the average value of the likelihood ratio with respect to the patterns in class i, plus the average value of the likelihood ratio with respect to the patterns in class j (Swain and Davis, 1978). If the classes are assumed to have normal density functions N (U,Σ) the expression can be written as

$$D_{ij} = \tfrac{1}{2}tr[(\Sigma_i - \Sigma_j)(\Sigma_i^{-1} - \Sigma_j^{-1})] + \tfrac{1}{2}tr[(\Sigma_i^{-1} - \Sigma_j^{-1})(U_i - U_j)(U_i - U_j)^T]$$

The first term is the difference between the covariance matrices of the two classes, the second measures the weighted difference between the means.

Divergence is not however directly related to P_ε and the probability of correct classification. The second term of the divergence expression continues to increase as long as the distance between the means increases. whereas the probability of correct classification can increase only to

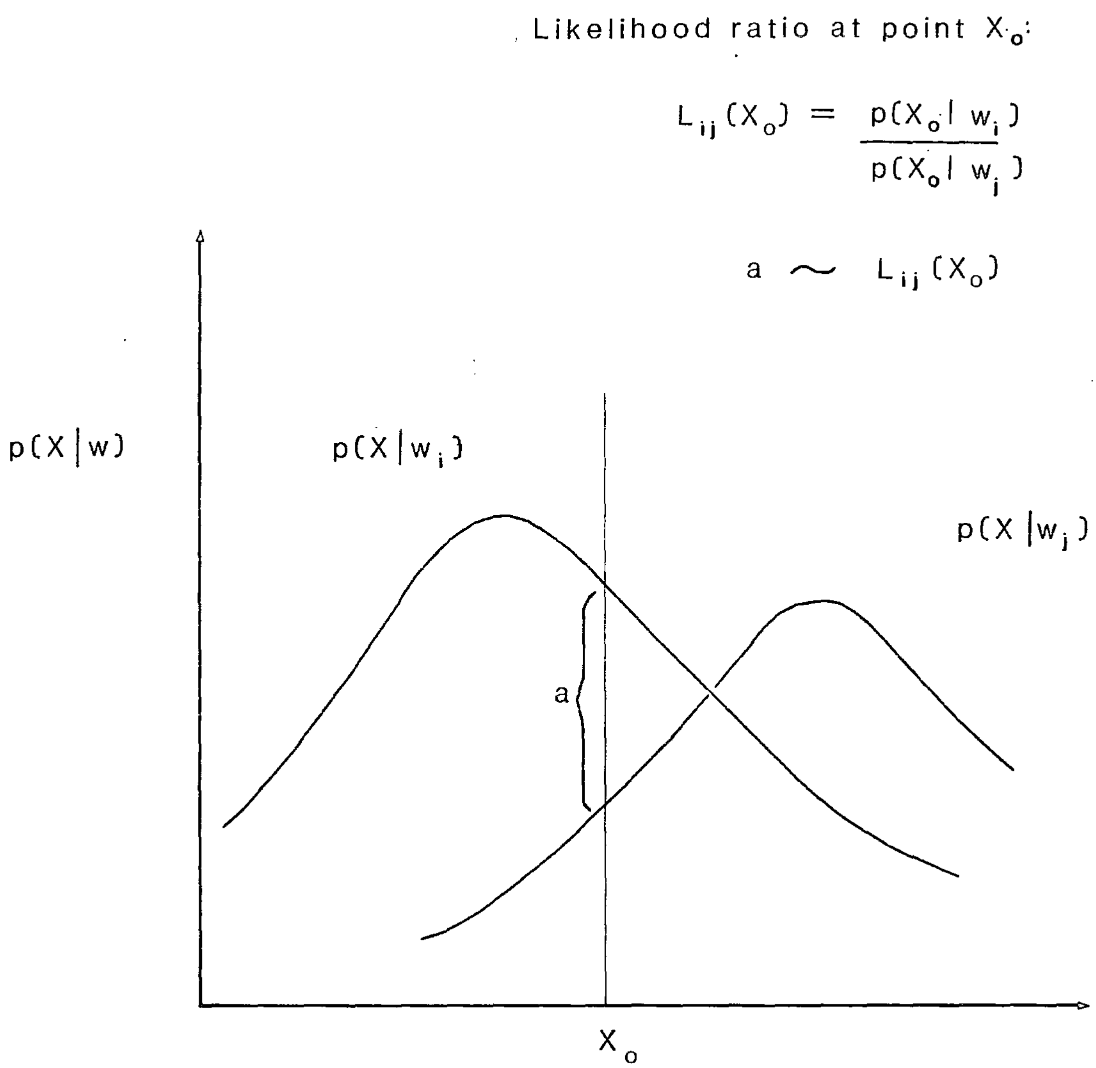


Figure 5.4 Definition of the likelihood ratio at a point. As the interval a increases, P_ϵ in assigning X_o to its correct class i decreases. After Swain and Davis (1978).

unity. A transformation of the divergence value to include a negative exponential term was found by Swain and King (1973), referenced in Swain and Davis (1978), to have a saturating curve closer to that of the probability of correct classification. This expression is the Transformed Divergence (TD) and is defined as

$$TD = 2\left[1 - \exp(-D_{ij}/8)\right]$$

In the computation used here the values of TD range from 0 to 2000, at which point the probability of correct classification approaches unity. Dean and Hoffer (1983) and Yool _et al_. (1986) amongst others have examined the relationship between TD and classification accuracy as part of other work. Dean and Hoffer concluded that TD is a relatively insensitive measure for estimating the probability of correct classification although the differences in accuracy in their data spanned only a few percentage points. Yool _et al_., in an examination of the single band case, concluded that the normality requirement of the divergence measure means that it may not be a reliable indicator of performance.

Although these studies are rather inconclusive it is accepted in this work that TD is a measure of separability and not of classification accuracy per se. The decision to use the TD measure was taken on practical grounds, the results of the analysis are interpreted in accordance with its limitations. A TD value of 1600 is taken to correspond to an accuracy level of approximately 70% (Townshend, pers. comm.) and, given the comments above, is used in this work to define an acceptable level of separation between distributions. The TD was calculated for all pairs of training sets for all combinations of wavebands. In most cases the divergence figures were examined for specific pairs of training sets and not grouped.

The program to calculate Transformed Divergence was provided by Ashbindu Singh and Andrew Harrison (Indian Forest Service and Bristol University respectively, both formerly of Reading University) and modified by the author.

5.4 Discriminating information in individual ATM bands.

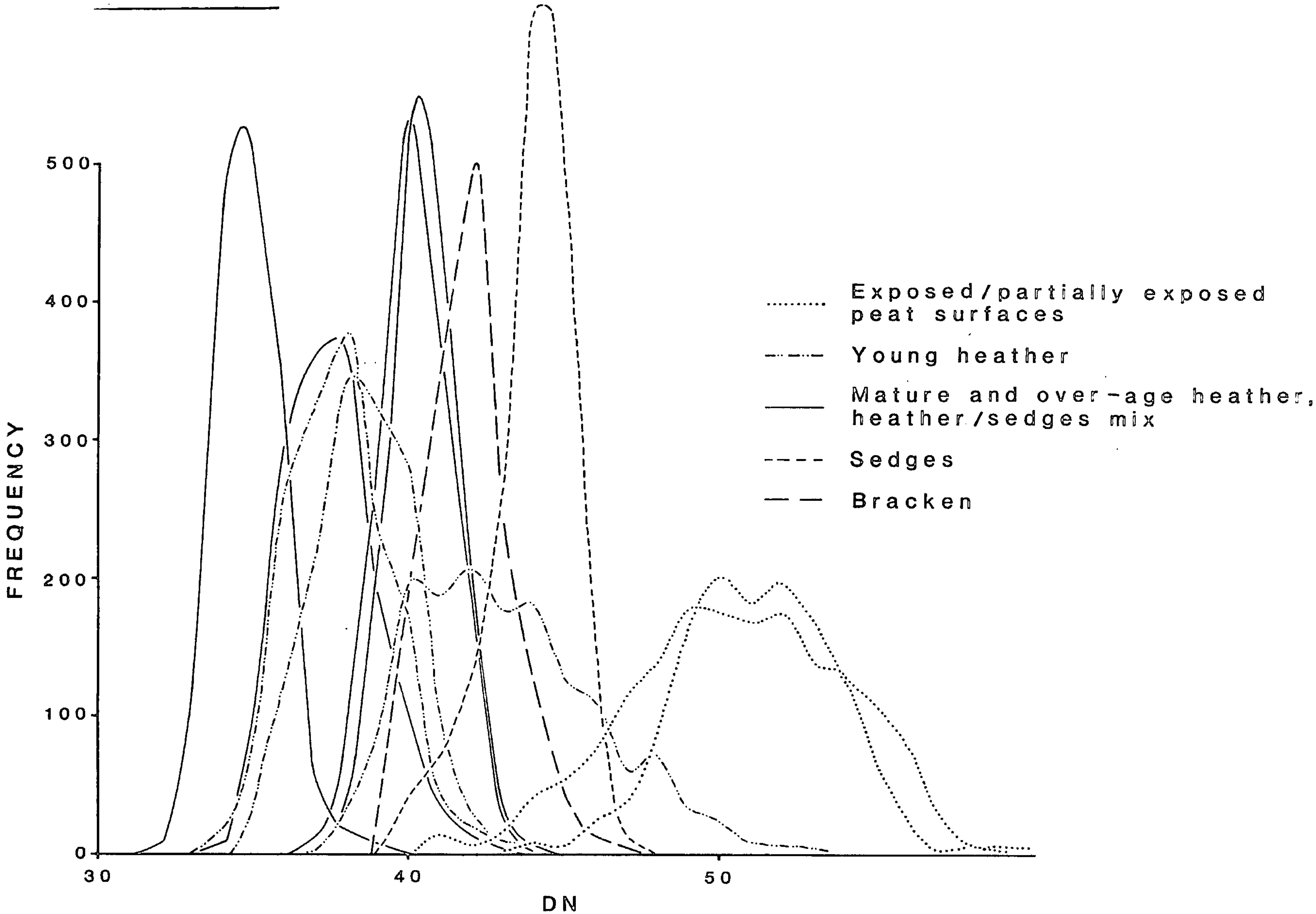
5.4.1 ATM 2

The absolute range of response in the blue wavelengths of ATM 2 is small. There is a single clear division of the histogram into vegetated and wholly or partially exposed sites (figure 5.5). Within the former the stands of Eriophorum and mature heather are isolated at the upper and the lower limits of response respectively. All other heather stands and the bracken areas are grouped between these two extremes. This distribution confirms the limited information available from the ground radiometer measurements.

As expected, each of the regenerating surfaces shows considerable internal variation in response and they are not well separated from each other or from a number of the vegetated classes (table 5.2). The regenerating sites which approach or have attained a full cover of young heather (sites 9,10 and 12) have a reduced and more uniform response and this trend is continued in the mature canopy. The over-age canopies however deviate from this pattern and have an unexpectedly high DN in this band. Their spectral response is not distinct from that of the young heather stands although the distinction is clear at the ground and critical in management terms. As discussed previously, reflectance in the blue wavebands depends on the relative amounts of green vegetation and substrate visible, the productivity of the vegetation, and the type of substrate. In the over-age stands the amount of green vegetation and the productivity are both low and the upper parts of the canopy have fallen back to expose the substrate. The combined effect of these features at the test sites is apparently to mimic the response of the younger stands, a result also found by Curran (1983).

It is clearly not possible to separate and identify all the important

Figure 5.5 SPECTRAL RESPONSE OF TEST SITES, ATM 2



Site	Minimum DN	Maximum DN	Mean	Standard deviation	Coefficient of variation
1	39	44	41.72	0.788	1.889
4	34	60	51.92	4.031	7.764
5	40	60	51.04	3.224	6.317
6	40	56	48.27	3.095	6.412
7	38	71	47.47	3.152	6.640
9	38	54	44.15	2.924	6.623
10	34	53	38.90	1.929	4.959
12	35	45	39.57	1.622	4.099
14	33	58	35.92	1.499	4.173
17	38	45	41.44	1.063	2.565
18	37	47	41.22	1.233	2.991
19	39	53	43.01	1.745	4.057
20	36	72	40.87	1.521	3.722
22	34	49	38.69	1.471	3.802
23	40	64	45.22	2.395	5.296

Table 5.2a Descriptive statistics of response at test sites, ATM 2

Class	4	5	6	7	9	10	12	14	17	18	19	20	22	23
1	1.64	1.73	1.15	0.96	0.25	1.20	1.10	2.38	0.80	0.64	0.02	0.70	1.47	0.59
4	-	0.12	0.53	0.63	1.14	2.18	2.17	2.89	1.30	2.03	1.54	1.99	2.40	1.04
5		-	0.46	0.58	1.14	2.36	2.37	3.20	1.34	2.20	1.62	2.14	2.63	1.04
6			-	0.12	0.69	1.85	1.83	2.68	0.72	1.61	1.07	1.59	2.09	0.54
7				-	0.55	1.67	1.64	2.46	0.52	1.40	0.89	1.39	1.88	0.39
9					-	1.07	0.99	1.85	0.25	0.68	0.22	0.72	1.24	0.22
10						-	0.19	0.87	1.97	0.73	1.12	0.57	0.10	1.46
12							-	1.17	1.95	0.58	1.02	0.41	0.32	1.41
14								-	3.38	1.94	2.18	1.64	0.87	2.39
17									-	1.58	0.70	1.54	2.38	0.04
18										-	0.60	0.13	0.97	1.10
19											-	0.66	1.36	0.53
20												-	0.76	1.11
22													-	1.70

Table 5.2b Dnorm values: spectral separation of test sites, ATM 2

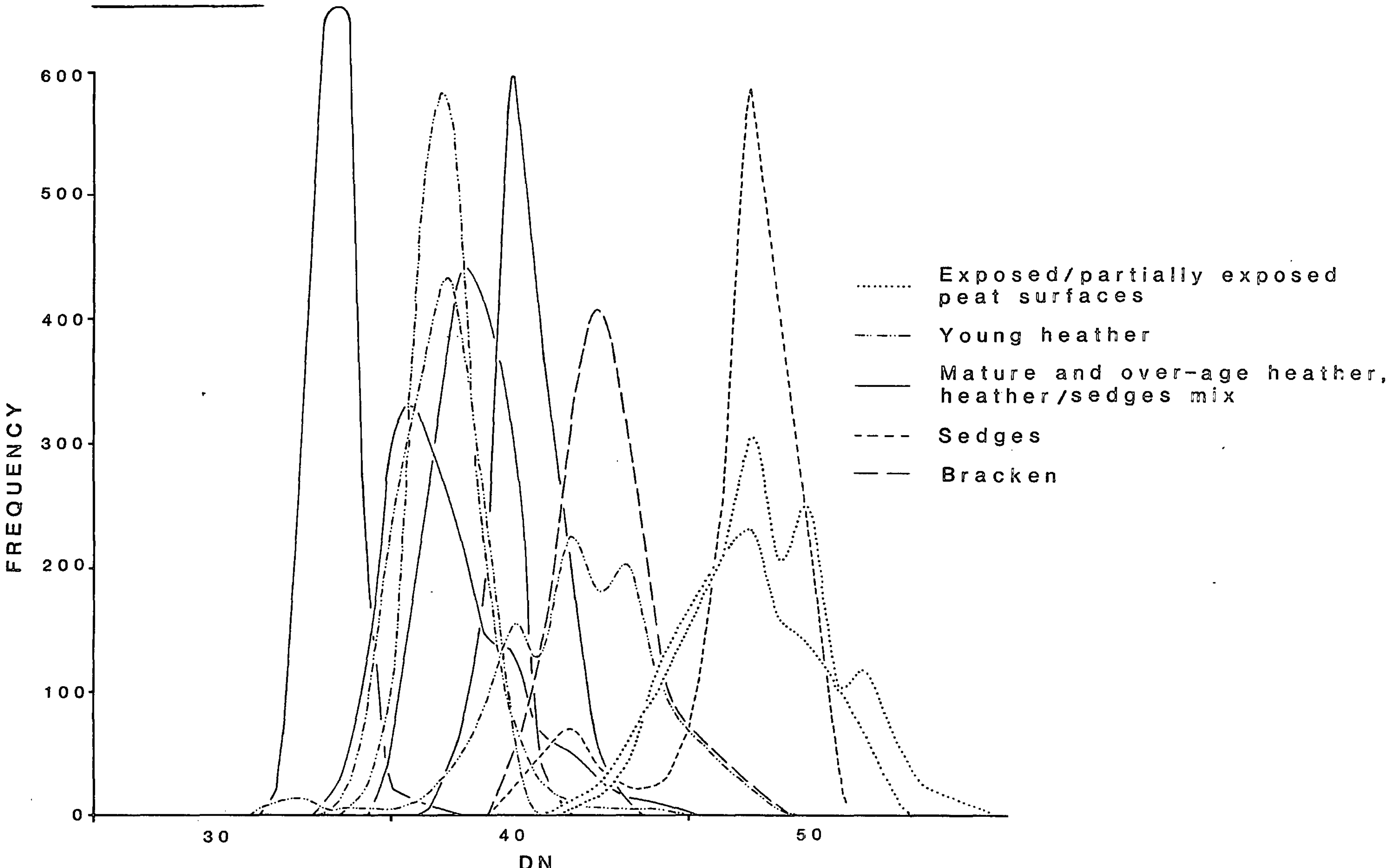
components of the moorland community in this band. In particular more spectral information is needed if the sedges and particularly the bracken classes are to be isolated from the broad heather class and the heather class is to be split into its component parts.

5.4.2 ATM 3

The distribution of the test sites in ATM 3 shows the same general structure as ATM 2 (fig 5.6). The mature heather canopy is separated more clearly from all other samples. The sedges site is distinct from the body of the heather classes, but this has the effect of placing it firmly with the two regenerating surfaces. Apart from these differences, the separation of the means of all classes is similar to that in ATM 2 (table 5.3). There is a slight but consistent reduction in the internal variation of each class, which means that, on average, their statistical separation is increased (table 5.3). This reduction in internal variation could be considered a loss of information, as the sensitivity to subtle variations within each class is apparently reduced. In practice however the test sites represent the finest desirable divisions of the moorland vegetation. The aim is therefore to maximise their separation rather than to seek additional information on their contents.

Compared to ATM 2 the regenerating surfaces (sites 5 - 8) and the young heathers (sites 9,10 and 12) form a more clearly defined part of the continuum from exposed surface to full cover, and the two regenerating peat surfaces have virtually identical signatures in this waveband. The pattern of decreasing DN with increasing vegetation through the heather stands is similar to that of ATM 2 and there is a similar overlap between the responses of the over-age and the young heather stands. The similarities in response between ATM2 and ATM3 are expected as the response in both bands is controlled by the same basic features of the vegetation.

Figure 5.6 SPECTRAL RESPONSE OF TEST SITES, ATM 3



Site	Minimum DN	Maximum DN	Mean	Standard deviation	Coefficient of variation
1	44	48	46.64	0.709	1.520
4	37	61	52.71	3.809	7.226
5	42	59	53.04	2.249	4.240
6	44	55	51.24	1.712	3.341
7	40	73	50.32	2.884	5.731
9	40	61	48.46	3.351	6.915
10	39	53	42.97	1.376	3.202
12	39	48	42.61	1.316	3.088
14	37	57	39.04	1.228	3.145
17	42	49	45.44	1.149	2.529
18	39	53	43.56	1.340	3.076
19	42	60	45.99	2.682	5.832
20	39	70	43.85	1.210	2.759
22	38	52	42.81	1.998	4.667
23	45	68	52.81	2.711	5.133

Table 5.3a Descriptive statistics of response at test sites, ATM 3

Class	4	5	6	7	9	10	12	14	17	18	19	20	22	23
1	0.80	1.18	0.84	0.44	0.04	1.68	1.83	3.07	1.28	1.51	0.51	1.48	1.40	1.01
4	-	0.05	0.27	0.36	0.59	1.88	1.97	2.71	0.05	1.78	1.03	1.77	1.67	0.02
5		-	0.46	0.53	0.81	2.78	2.92	4.03	0.01	2.64	1.43	2.66	2.34	0.05
6			-	0.19	0.54	2.66	2.83	4.13	0.50	2.50	1.18	2.51	2.19	0.37
7				-	0.30	1.72	1.83	2.74	0.56	1.60	0.78	1.58	1.50	0.45
9					-	1.15	1.24	2.04	0.86	1.04	0.41	1.00	1.03	0.72
10						-	0.13	1.51	3.06	0.22	0.75	0.34	0.05	2.41
12							-	1.40	3.23	0.36	0.85	0.49	0.05	2.53
14								-	4.47	1.76	1.78	1.97	1.12	3.50
17									-	2.91	1.53	2.94	2.54	0.04
18										-	0.61	0.11	0.22	2.28
19											-	0.55	0.67	1.26
20												-	0.32	2.29
22													-	2.07

Table 5.3b Dnorm values: spectral separation of test sites, ATM 3

5.4.3 ATM 5

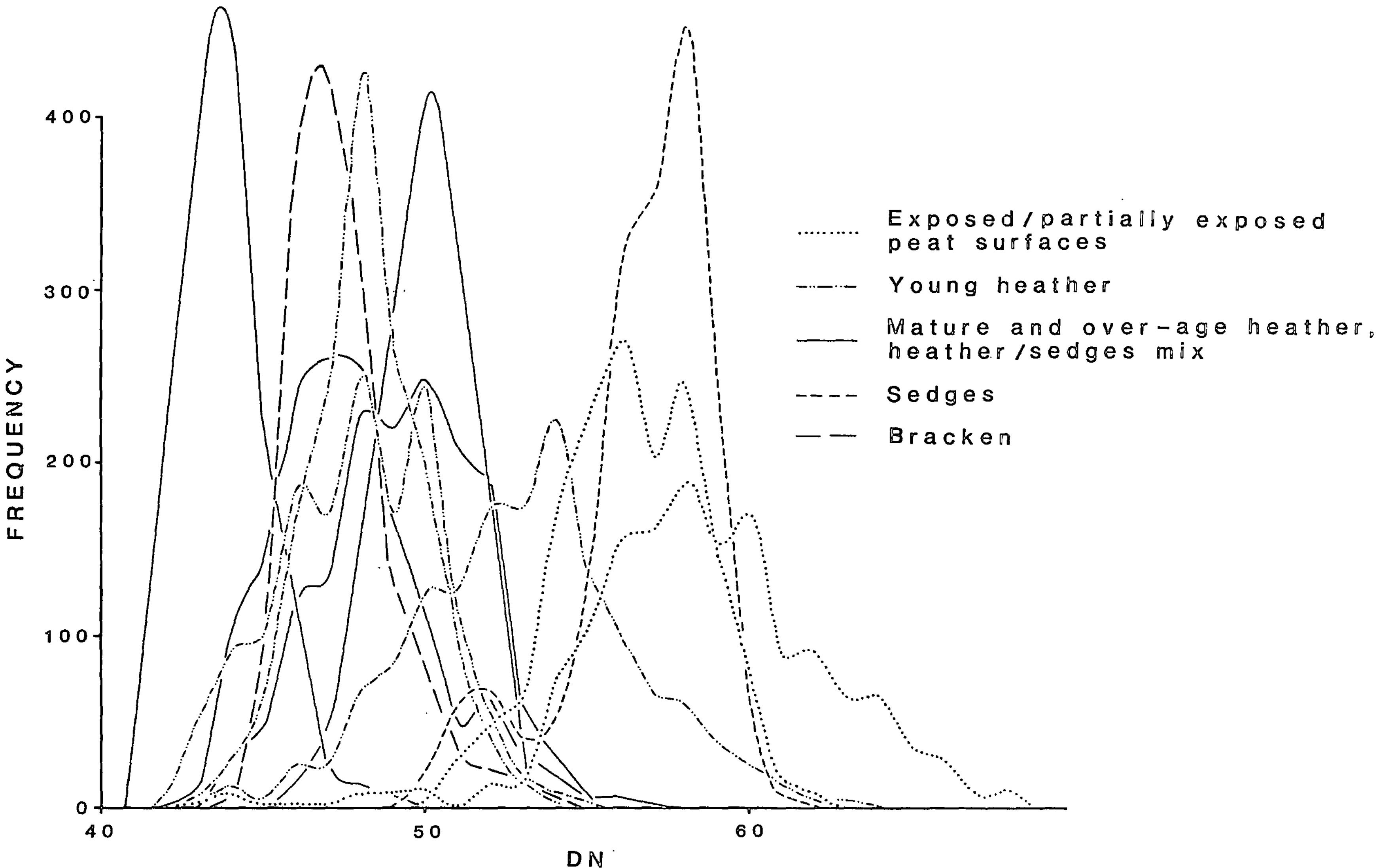
In comparison to ATM 2 and ATM 3 the response of the bracken class in ATM 5 is low, but in all other respects the ordering of the classes in ATM 5 is similar to that in the other two visible bands. The exposed and partially exposed peat surfaces have the highest radiance and, as in ATM 3, the sedges class and the partially vegetated sites have a similar mean response (figure 5.7). The positioning and separation of the heather canopies is similar to ATM 2 and ATM 3 and reflectance generally decreases with increasing green vegetation. The response of the bracken stand is however more closely aligned with the mature heather stand and the areas of full young heather cover than with the over-age heather stands in this waveband (table 5.4).

In most cases the separation of the class means is slightly higher in ATM 5 than it is in ATM 2 or ATM 3. However the variance within each training area is also substantially higher and this outweighs the wider spacing of the means so that there is considerable overlap between classes in this waveband (figure 5.7, and compare tables 5.4 and 5.3).

As noted in chapter 2, ATM 5 is at the point of maximum sensitivity to chlorophyll concentration, and it is expected to be sensitive to slight differences in features of the canopy or in the amount of vegetation cover. At these sites this means that the red band has identified both the differences between classes and the detail within each class. This result was also found in the ground radiometer data. As noted in section 5.4.2, the identification of fine scale variation in the canopies is not particularly helpful in this environment. However, the 30m resolution of satellite TM data should remove some of the within class variance whilst maintaining the separation of the means, in which case the distribution of variance across the data set will be improved. On this basis the red band is expected to be the most useful of the visible bands for discriminating the elements of the moorland community.

In summary, the three visible bands show similar patterns of response over

Figure 5.7 SPECTRAL RESPONSE OF TEST SITES, ATM 5.



Site	Minimum DN	Maximum DN	Mean	Standard deviation	Coefficient of variation
1	43	49	46.89	0.664	1.416
4	42	71	59.32	4.220	7.114
5	43	64	57.28	2.325	4.068
6	50	62	56.52	1.824	3.220
7	43	74	55.84	3.028	5.426
9	42	67	53.95	3.444	6.528
10	43	59	49.22	1.962	3.982
12	41	55	48.87	2.554	5.218
14	41	65	44.84	1.694	3.769
17	46	55	51.03	1.475	2.900
18	44	63	50.33	2.332	4.629
19	46	62	52.76	2.437	4.625
20	45	71	52.17	1.909	3.661
22	43	59	48.62	2.236	4.607
23	50	74	57.86	2.689	4.649

Table 5.4a Descriptive statistics of response at test sites, ATM 5

Class	4	5	6	7	9	10	12	14	17	18	19	20	22	23
1	1.77	2.14	2.22	1.56	1.04	0.19	0.09	1.05	2.59	0.45	1.01	0.99	0.03	2.09
4	-	0.28	0.43	0.46	0.68	1.60	1.52	2.42	0.19	1.34	0.96	1.14	1.57	0.18
5		-	0.18	0.27	0.58	1.88	1.72	3.09	0.17	1.49	0.95	1.21	1.80	0.12
6			-	0.14	0.49	1.92	1.75	3.31	0.40	1.49	0.88	1.16	1.83	0.30
7				-	0.30	1.35	1.27	2.38	0.44	1.05	0.58	0.76	1.33	0.36
9					-	0.87	0.85	1.77	0.76	0.63	0.20	0.33	0.90	0.64
10						-	0.08	1.20	2.28	0.26	0.80	0.76	0.13	1.86
12							-	0.95	2.06	0.30	0.78	0.74	0.05	1.72
14								-	3.67	1.36	1.92	2.03	0.91	2.97
17									-	1.82	1.21	1.53	2.15	0.03
18										-	0.51	0.43	0.35	1.50
19											-	0.13	0.84	1.00
20												-	0.81	1.24
22													-	1.79

Table 5.4b Dnorm values: spectral separation of test sites, ATM 5.

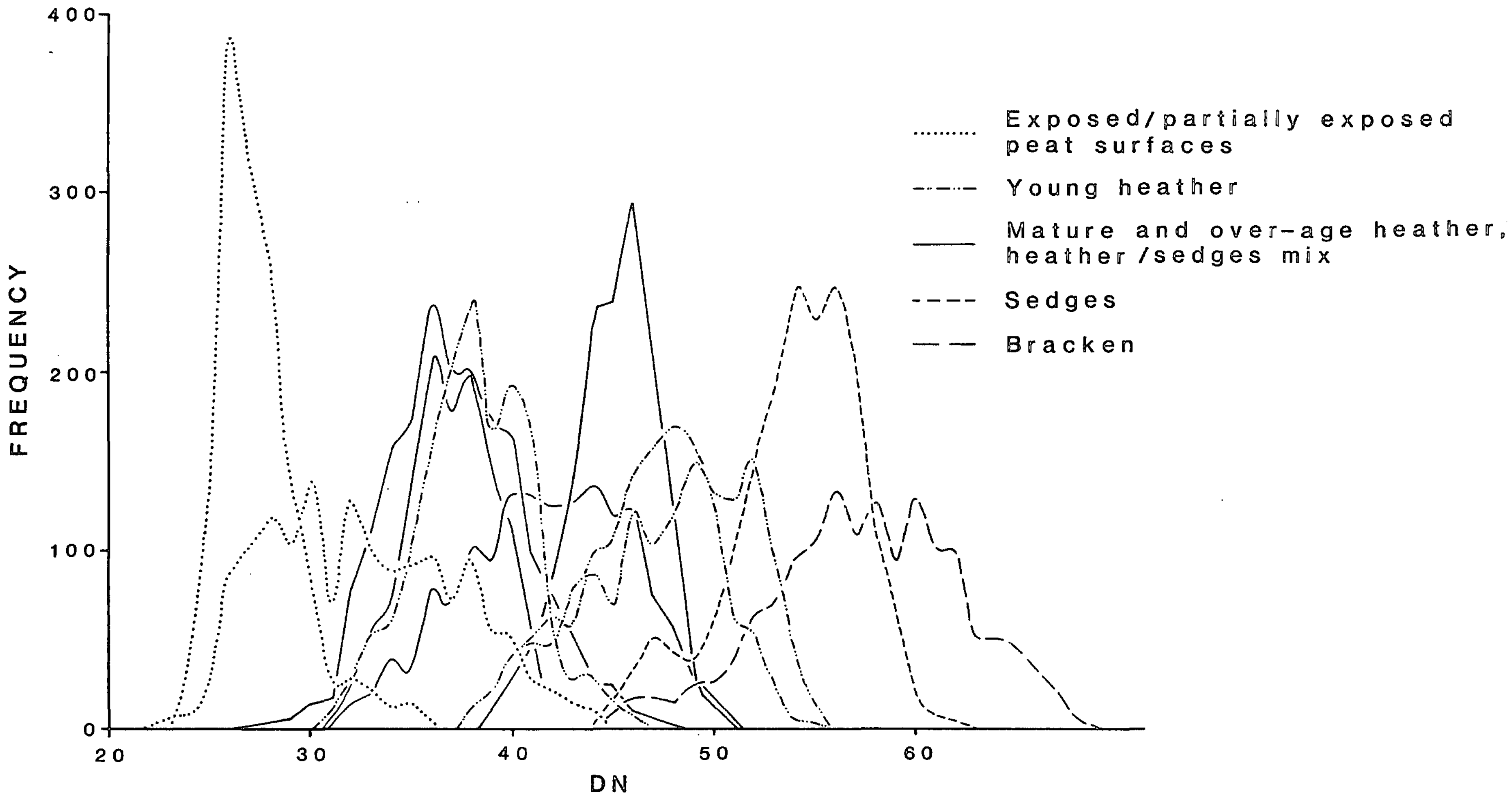
these samples of moorland vegetation, and they have high positive correlations at a number of test sites (see section 5.5). The discriminatory information available in one waveband is most often duplicated somewhere in the other two. The most obvious differences between the bands lie in the response of the bracken and the sedges stands relative to the heathers and each other, although these differences are not sufficient to isolate either species. The only vegetation type that can be distinguished from all others with an acceptable accuracy is the mature heather stand. A combination of the visible wavebands would not therefore isolate all the major canopies or make the remaining critical sub-divisions of the heather class as described in chapter 3. There are also overall differences between the wavebands in the amount of within class variance, and detailed differences in the separation of specific canopies.

5.4.4 ATM 7

The response of the test sites in this waveband is expected to be ordered roughly by biomass, with the highest DN in the stands of highest biomass and the lowest readings over the exposed peat surfaces, although differences in the leaf and canopy structure may preclude this. The details of the intervening distribution will be described by differences in the proportions of green and brown biomass and the species composition of the stand. Because of the sensitivity of the near-IR to the presence and abundance of vegetation, a high within class variance is expected for most classes.

Figure 5.8 shows that most of these expectations are met. Compared to the visible bands the ordering of the vegetated and non-vegetated sites is approximately reversed. The response of both the bracken and the sedges stands is however substantially separate from all other classes, although there is some overlap between these two sites and between the response from the sedges and site 10, of full young heather cover (table 5.5, figure 5.8). In the visible bands, the sedges are confused with the partially

Figure 5.8 SPECTRAL RESPONSE AT TEST SITES, ATM 7



Site	Minimum DN	Maximum DN	Mean	Standard deviation	Coefficient of variation
1	44	68	59.97	2.909	4.851
4	24	41	28.50	2.311	8.109
5	18	51	33.72	4.653	13.799
6	25	59	35.85	6.543	18.251
7	21	55	37.79	5.520	14.607
9	20	56	46.12	5.361	11.624
10	21	63	38.99	3.844	9.859
12	29	57	48.57	4.376	9.010
14	25	47	37.28	2.671	7.165
17	33	52	45.91	2.443	5.321
18	30	53	42.64	4.073	9.552
19	29	60	48.42	3.739	7.722
20	31	56	46.01	3.803	8.266
22	30	50	38.97	2.877	7.383
23	34	63	54.68	3.985	7.288

Table 5.5a Descriptive statistics of response at test sites, ATM 7

Class	4	5	6	7	9	10	12	14	17	18	19	20	22	23
1	3.71	2.35	1.77	1.76	1.05	1.99	0.92	2.48	0.28	1.57	1.00	1.25	2.22	0.32
4	-	0.75	0.86	1.22	2.37	1.70	3.00	1.76	5.18	2.21	3.29	2.86	1.06	1.11
5		-	0.22	0.43	1.28	0.62	1.64	0.49	2.88	1.02	1.75	1.45	0.68	2.43
6			-	0.16	0.86	0.27	1.13	0.12	2.02	0.61	1.18	0.94	0.28	1.74
7				-	0.77	0.10	1.05	0.10	2.05	0.47	1.11	0.84	0.09	1.74
9					-	0.82	0.23	1.16	1.11	0.40	0.23	0.04	0.92	0.90
10						-	1.17	0.26	2.44	0.46	1.24	0.92	0.02	2.00
12							-	1.60	0.94	0.70	0.02	0.31	1.33	0.73
14								-	3.26	0.80	1.74	1.35	0.28	2.61
17									-	1.83	1.05	1.40	2.84	0.10
18										-	0.74	0.43	0.54	1.49
19											-	0.32	1.43	0.81
20												-	1.06	1.11
22													-	2.29

Table 5.5b Dnorm values: spectral separation of test sites, ATM 7

vegetated areas and the bracken class overlaps with the mature heather stand. The visible and the near-IR bands therefore contain complementary information for these sites and their use together will increase the accuracy with which these stands can be discriminated (figure 5.9).

The fully exposed peat surface has a low and uniform DN in this waveband. DN increases with increasing vegetation through the regenerating and the young heather stands, all of which have a high internal variation in response (table 5.5). The near-IR distinguishes between two areas of full young heather growth (sites 10 and 12) which have overlapping responses in the visible bands. There are only slight differences between the two areas at the ground and there is no clear reason for this separation.

As in the visible bands the relationship between ecological descriptors and spectral response is not straight forward, as the response of the mature and the over-age canopies in this waveband is considerably lower than that of the young heathers, and adjacent in spectral terms to the fully exposed peats and the regenerating surfaces. The confusion between areas of full young heather growth and stands of over-age heather therefore remains in the near-IR although the Dnorm values between specific pairs of sites are higher in this waveband, and the average separation of the two classes over all training areas is also increased (table 5.5). Given the variety of vegetation on the moors however this slight improvement is of little practical significance and the problem remains that canopies which are fundamentally different in ecological terms are giving a very similar spectral response.

In summary, the exposed surfaces and the heather, bracken and sedges stands are separated more clearly in the near-IR than in the visible bands. Within the heather class, the three samples of young heather are separated from each other but have a similar response to some of the over-age stands. Apart from this splitting of the young heather canopies, the relative positions of the heather stands are similar to those in the visible bands despite the different controls on radiance in these two parts of the

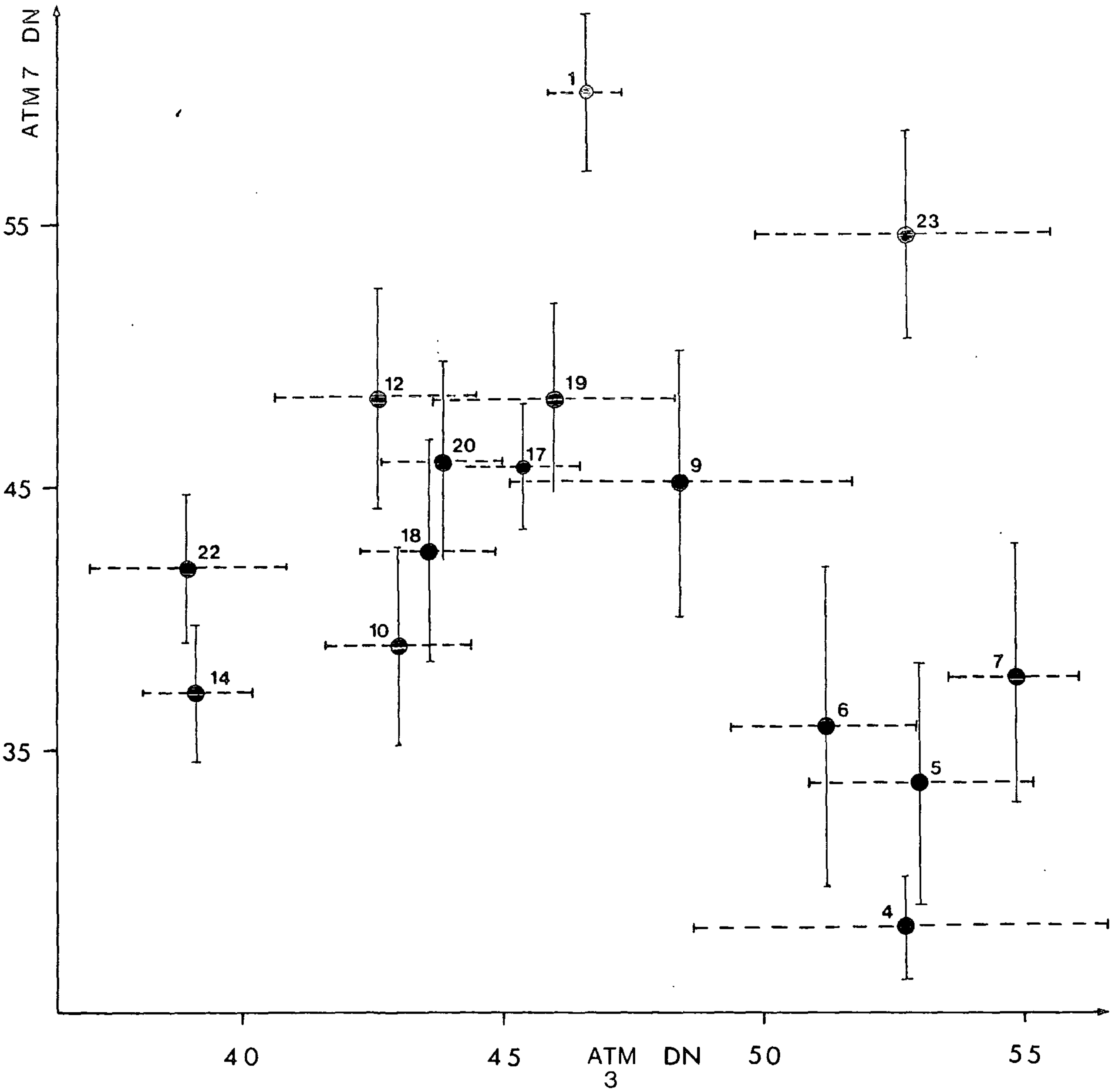


Figure 5.9 Spectral response of selected test sites in visible (ATM 3) and near-IR (ATM 7) wavebands, September 1983 ATM data.

spectrum.

The ground radiometer data showed a general increase in near-IR reflectance with vegetation amount. The fuller sample available from the ATM data suggests that this relationship is not straight-forward although it is true in the broadest terms. The discrepancies arise from the position of the young heather stands relative to the mature and over-age heathers.

The near-IR band clearly holds at least some different information to the visible bands. Fig 5.9 is analogous to figure 4.11 for the ground radiometer data and shows how these differences can be used to isolate some of the elements of the moorland community.

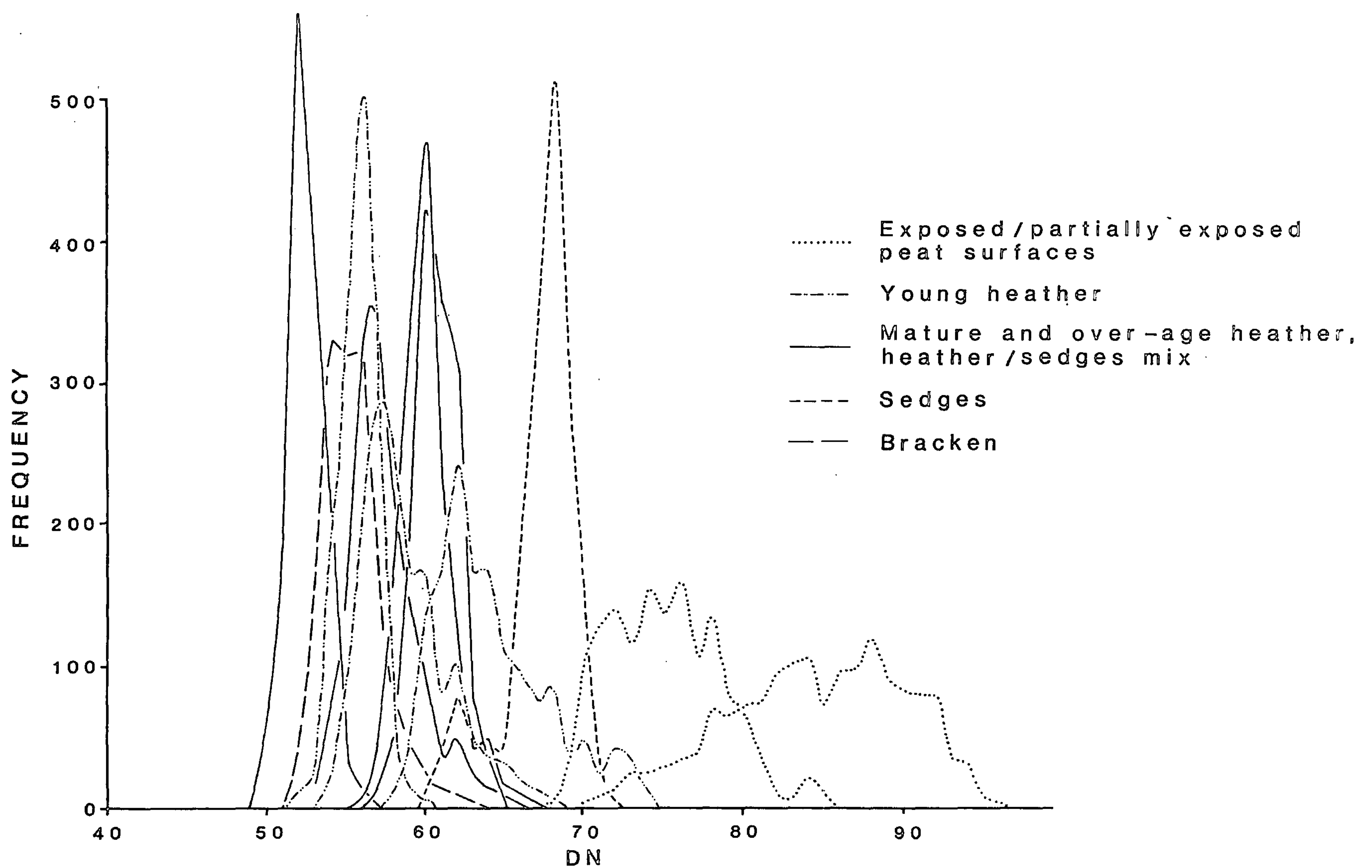
5.4.5 ATM 9 and ATM 10

The ATM 9 data are of very poor quality and contain substantial amounts of noise. This is apparently due to a technical problem in data acquisition. The discussion below therefore concentrates on the ATM 10 data. The pattern of response in ATM 9 is similar to that in ATM 10 but shows a much higher internal variation in each training set (tables 5.6, 5.7).

The pattern of response in the mid-IR bands is similar to that of the visible bands. The fully and partially exposed surfaces are clearly separated from the vegetated sites and the vegetated sites are also quite well separated from each other. The internal variation in each of the vegetated classes is slightly above that in the visible bands but considerably less than that in the near-IR. (table 5.6).

The response of the areas of young heather and the over-age stands intermingle although, because of the variety of response within each class, most individual sites are clearly separated from each other (figure 5.10). The areas of full young cover (sites 10 and 12) are distinct from those where cover is still incomplete (site 9) and there is a similar variation in the response of the over-age canopies. Pixels from sites 9 and 10 are most likely to be confused with the over-age stands.

<u>Figure 5.10</u> SPECTRAL RESPONSE AT TEST SITES, ATM 10



Site	Minimum DN	Maximum DN	Mean	Standard deviation	Coefficient of variation
1	29	50	38.997	2.785	7.142
4	31	59	48.083	3.951	8.217
5	33	63	52.731	3.457	6.600
6	36	61	46.993	3.693	7.858
7	31	65	47.110	4.051	8.599
9	27	57	43.611	3.660	8.392
10	31	55	40.090	3.149	7.855
12	29	47	37.802	2.660	7.026
14	25	57	34.888	2.707	7.758
17	34	51	41.885	2.601	6.209
18	32	58	40.670	2.789	6.858
19	31	53	40.766	3.151	7.729
20	33	55	44.002	2.758	6.268
22	26	51	39.467	3.136	7.946
23	36	62	49.532	3.455	6.974

Table 5.6a Descriptive statistics of response at test sites, ATM 9

Site	Minimum DN	Maximum DN	Mean	Standard deviation	Coefficient of variation
1	53	60	56.55	1.122	1.984
4	53	86	75.25	4.580	6.086
5	63	99	85.30	5.803	6.803
6	61	91	78.04	6.198	7.942
7	59	97	74.53	6.297	8.449
9	57	83	65.54	4.094	6.247
10	54	87	60.24	3.974	6.597
12	53	65	56.83	1.325	2.332
14	50	81	53.67	1.820	3.391
17	57	68	61.72	1.395	2.260
18	57	76	61.12	1.851	3.028
19	57	73	61.23	2.243	3.663
20	57	84	62.37	1.694	2.716
22	48	73	58.38	2.082	3.566
23	60	92	68.56	3.376	4.924

Table 5.6b Descriptive statistics of response at test sites, ATM 10

Class	4	5	6	7	9	10	12	14	17	18	19	20	22	23
1	1.35	2.20	1.23	1.19	0.73	0.16	0.27	0.75	1.83	0.30	0.30	0.90	0.08	1.69
4	-	0.63	0.14	0.12	0.58	1.13	1.59	1.98	0.24	1.10	1.03	0.61	1.20	0.20
5		-	0.28	0.25	1.27	1.91	2.48	2.89	0.45	1.93	1.81	1.40	1.98	0.46
6			-	0.02	0.45	1.02	1.49	1.89	0.41	0.98	0.91	0.46	1.09	0.36
7				-	0.45	0.98	1.42	1.81	0.37	0.94	0.88	0.46	1.05	0.32
9					-	0.54	0.97	1.39	0.90	0.47	0.43	0.05	0.61	0.82
10						-	0.41	0.86	1.55	0.12	0.13	0.68	0.08	1.43
12							-	0.50	2.12	0.57	0.55	1.19	0.33	1.96
14								-	2.56	1.05	1.00	1.67	0.77	2.38
17									-	1.54	1.44	0.98	1.63	0.04
18										-	0.62	0.60	0.20	1.42
19											-	0.55	0.20	1.33
20												-	0.76	0.89
22													-	1.51

Table 5.7a Dnorm values: spectral separation of test sites, ATM 9

Class	4	5	6	7	9	10	12	14	17	18	19	20	22	23
1	2.91	3.75	2.63	2.18	1.50	0.66	0.47	0.72	3.19	1.26	1.17	1.66	0.50	2.31
4	-	0.97	0.23	0.08	1.15	1.76	3.12	3.37	1.04	2.20	2.05	2.47	2.49	0.84
5		-	0.63	0.90	2.02	2.56	3.99	4.15	2.18	3.16	2.99	3.06	3.37	1.82
6			-	0.32	0.85	1.50	2.07	3.00	1.13	2.06	1.95	1.94	2.30	0.96
7				-	0.45	0.98	1.42	2.54	0.71	1.62	1.53	1.50	1.87	0.60
9					-	0.63	1.58	1.98	0.53	0.71	0.65	0.52	1.11	1.43
10						-	0.64	1.13	1.41	0.15	0.16	0.38	0.29	1.13
12							-	1.00	1.80	1.35	1.23	1.83	0.46	2.50
14								-	3.99	2.03	1.86	2.47	1.19	2.87
17									-	1.97	1.76	1.71	2.47	0.01
18										-	0.03	0.35	0.67	1.42
19											-	0.29	0.63	1.31
20												-	1.02	1.22
22													-	1.82

Table 5.7b Dnorm values: spectral separation of test sites, ATM 10

The mixed heather/sedges site and site 10 overlap in ATM 10 as they do in the visible bands, but these sites are separated in the near-IR (figure 5.11). Similarly, although bracken overlaps the mature heather response in the mid-IR, the two are separated in the near-IR band. ATM 10 gives similar results to the visible bands for the isolation of the sedges and bracken stands. Compared to the visible bands it has a greater potential for separating the different elements of the heather class, especially when used in conjunction with the near-IR (figure 5.11).

5.4.6 ATM 11

The thermal-IR has a high absolute range in this data set. The highest readings are found over the exposed peat surfaces and DN decreases with increasing vegetation. All classes have a high internal variance (table 5.8). The means of the partially vegetated areas are particularly well separated from each other and all other sites but these sites also have an exceptionally high variance. The responses of the least vegetated peat surface and the completely exposed peat surface overlap and are considerably higher than that of any other regenerating area.

The thermal band differentiates between the three areas of young heather cover but with a different ordering and degree of separation to that in the near-IR and mid-IR bands. Site 12, a collecting point for sub-surface drainage is placed with the mature heather canopies. The other two (sites 10 and 9) overlap to span the gap to the first of the partially vegetated sites. Site 10 is on the edge of a deep peat lens which contains some standing water. Site 9 is on a peaty podsol substrate.

The bracken stand is clearly separated from all other sites at the lower limit of DN (figure 5.12). Three samples of bracken stands were taken and all showed this result. The mature heather canopy, the over-age heather canopies, the area of mixed heather and Eriophorum and site 12 of young heather overlap considerably to form a peak of DN between the bracken and the exposed surfaces. There is virtually no distinction between the

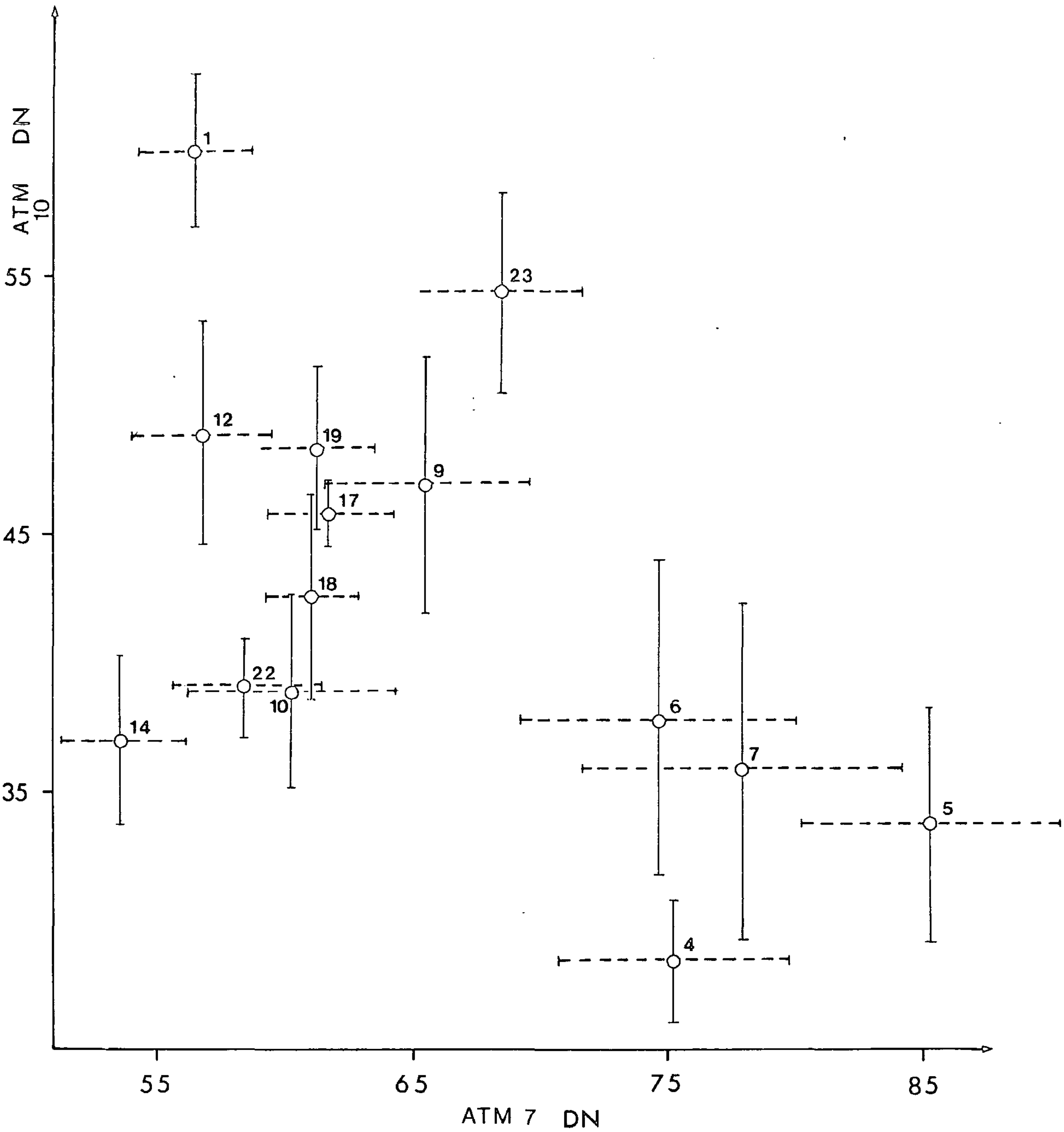
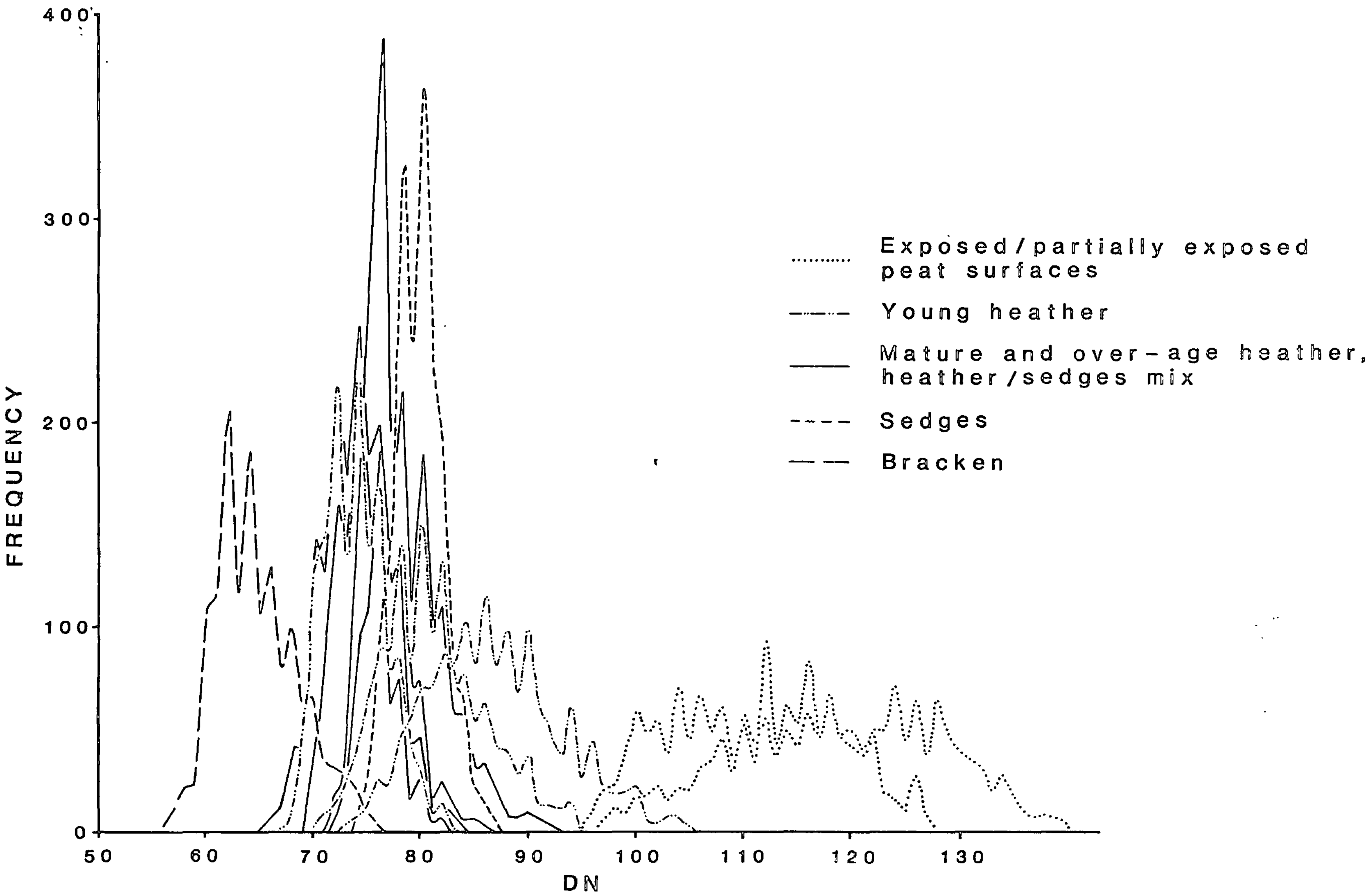


Figure 5.11 Spectral response of selected sites in mid-IR (ATM 10) and near-IR (ATM 7) wavebands, September 1983 ATM data.

Figure 5.12 SPECTRAL RESPONSE AT TEST SITES, ATM 11



Site	Minimum DN	Maximum DN	Mean	Standard deviation	Coefficient of variation
1	55	74	61.17	2.060	3.368
4	69	131	110.64	9.835	8.890
5	77	146	118.56	10.683	9.008
6	76	136	109.99	12.038	10.946
7	73	127	95.98	9.476	9.877
9	65	114	83.12	6.602	8.037
10	74	122	88.46	7.270	8.218
12	68	91	75.02	3.099	4.132
14	66	131	74.73	3.858	5.165
17	72	89	77.44	2.086	2.699
18	72	103	80.07	3.750	4.683
19	64	90	73.62	3.172	4.306
20	69	119	78.37	4.012	5.117
22	68	102	75.66	2.945	3.899
23	73	127	81.47	5.681	6.972

Table 5.8a Descriptive statistics of response at test sites, ATM 11

Class	4	5	6	7	9	10	12	14	17	18	19	20	22	23
1	3.87	3.41	2.56	2.05	1.44	1.85	1.11	0.97	2.06	1.63	0.92	1.38	1.27	1.46
4	-	0.39	0.03	0.76	1.67	1.30	2.75	2.62	2.78	2.25	2.85	2.33	2.74	0.52
5		-	0.41	1.13	2.08	1.68	3.16	3.01	2.96	2.67	3.24	2.74	3.08	0.27
6			-	0.63	1.43	1.08	2.26	2.17	2.02	1.84	2.34	1.92	2.18	1.57
7				-	0.80	0.43	1.62	1.55	1.29	1.17	1.72	1.27	1.54	0.93
8					-	0.42	0.79	0.76	0.25	0.25	0.92	0.40	0.67	0.10
9						-	1.30	1.23	0.85	0.76	1.42	0.89	1.19	0.54
10							-	0.04	1.03	0.74	0.22	0.47	0.19	0.73
12								-	0.95	0.70	0.16	0.46	0.21	0.71
14									-	0.07	1.28	0.34	0.81	0.13
17										-	0.93	0.22	0.57	0.15
18											-	0.66	0.41	0.89
19												-	0.31	0.32
20													-	0.60
22														

Table 5.8b Dnorm values: spectral separation of test sites, ATM 11

elements of this grouping. The grass canopy and the other young heather classes form a secondary peak with slightly higher DN values.

In summary, the major cover types of bracken, the exposed surfaces and the heathers can be identified in the thermal band although the sedges cannot be separated reliably from the last two (table 5.8). There is virtually no differentiation of the established heather canopies by their response in this waveband. The response of the three young stands (sites 9, 10 and 12) overlap with that of the Eriophorum stand, the exposed surfaces and the established heather stands respectively. These pairs of classes are however separable to some extent in the reflective wavebands. For the data examined it is not possible to separate the over-age heather stands as a group from all examples of the young heather cover.

5.4.7 Summary

It is clear that no single band can separate all components of the moorland community, but that the ATM wavebands do hold different discriminating information and individual training sets can be isolated in a simple multi-dimensional feature space, as shown in figures 5.9 and 5.11. This supports the original hypothesis as stated in section 5.1. The best separations occur where different sources of information- wavebands from different parts of the spectrum- are used (figure 5.18) and certain waveband combinations appear to be critical in some cases.

At least some of the components of the moorland community can therefore be isolated by their spectral response in the ATM wavebands examined here, which confirms the results of chapter 4. There is however considerable duplication in discriminating ability within and between the different spectral regions.

5.5 Duplication of discriminatory information.

Where this redundancy exists, one or more wavebands can be dropped from the analysis with no loss of discriminating information. For each pair or

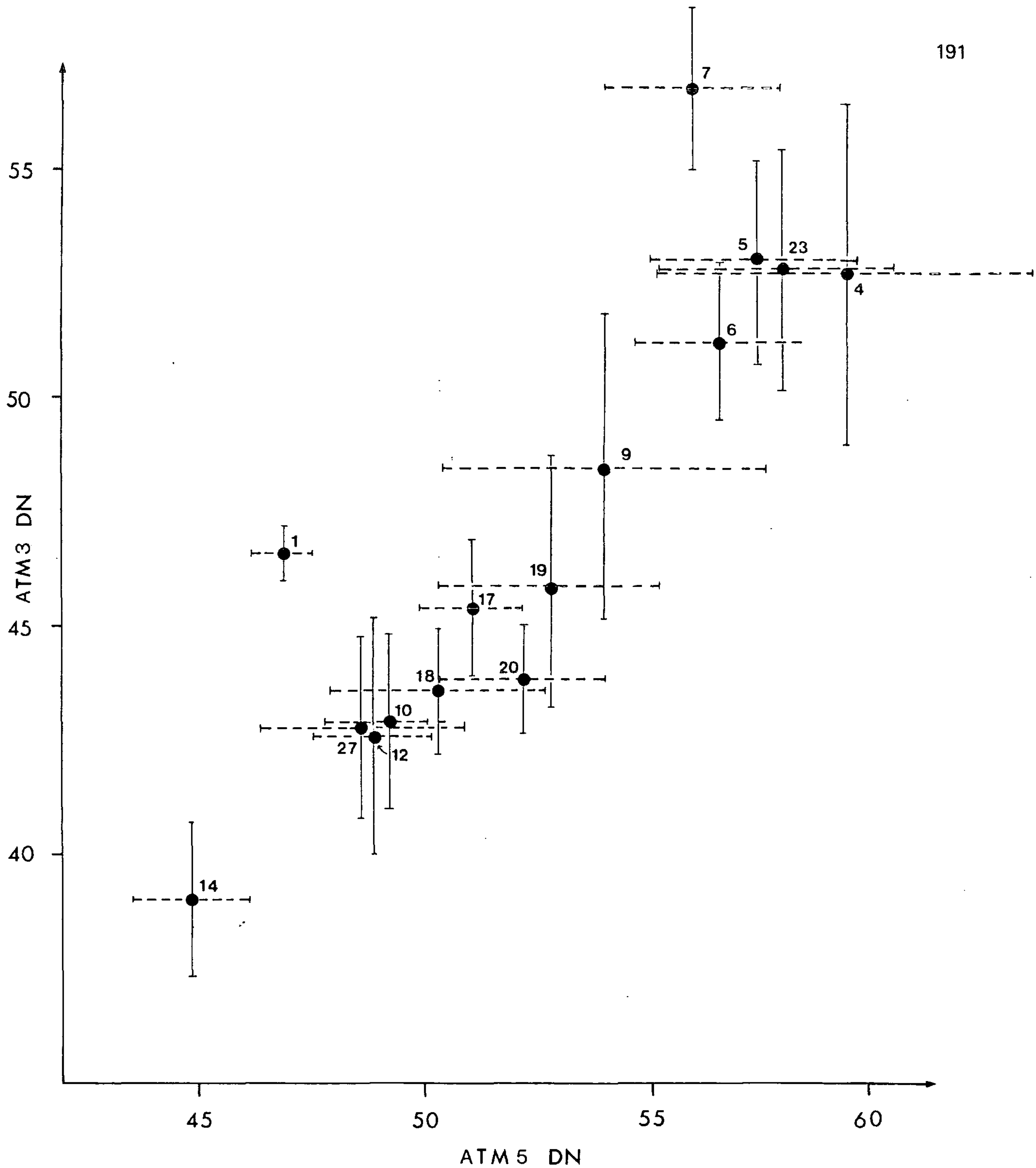

55
50
45
40
ATM3 DN
45
50
55
60
ATM5 DN
7
5
23
4
6
9
1
19
17
18
20
10
27
12
14

Fig 5.13a

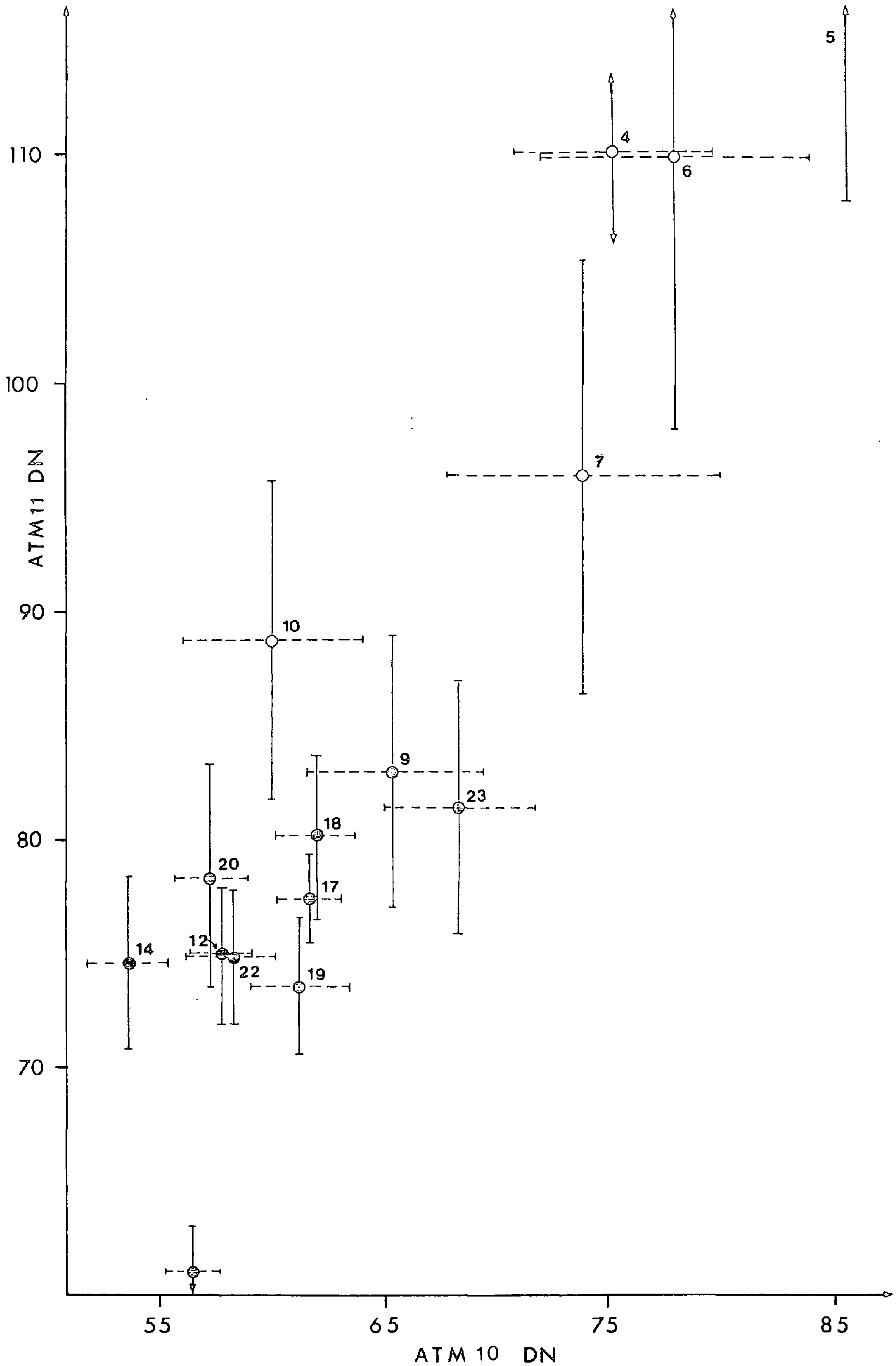


Figure 5.13 Spectral response of test sites in the feature space defined by
a. Two visible bands
b. Mid-IR and thermal IR bands.
Compare discriminating information with figures 5.9 and 5.11.

group of cover types therefore, a subset of wavebands may exist which retains the discriminatory information of the full data set in a reduced number of wavebands. This section and section 5.6 investigate and test this hypothesis, by identifying these optimum waveband combinations for the test sites described in section 5.4.

Replication of discriminatory information can be recognised to a certain extent by the presence of high inter-band correlations although the degree of correlation also depends on the absolute amount of variation in the image. High inter-band correlation is often used as a basis for selecting and discarding wavebands which have similar discriminating information. More accurately however these correlations show only that the spectral dimensions of the full feature space at the site can be reduced to a smaller number of independent axes whilst retaining a good description of the variance in the data. The change in actual discriminating information between the original and the reduced data set also depends on the absolute response of the target in these wavebands.

If two classes are clearly discriminated from each other by one band it is not important for that case that the remaining wavebands carry independent information. An additional class however which overlaps one or both of the original classes on these axes may be isolated only by a new and independent source of information. Where the elements of the spectral response at a site are uncorrelated, there are a number of different sources of variation in the target, any of which may be the critical one on which this site is separated from another. Therefore the higher the number of independent dimensions in the data, the more likely the class is to be separated from others, and the less spectral information will be needed to make each separation. This section examines the number and identity of the spectral dimensions needed to describe the response of each test site.

Table 5.9 lists the correlation matrices for a sample of the test sites. Over the whole scene, the visible bands are strongly correlated with each other and with the mid-IR. The second band of the mid-IR is positively

Site 1 bracken

3	.79					
5	.73	.84				
7	-.05	-.08	.23			
9	.23	.23	.30	.01		
10	.49	.51	.66	-.36	.32	
11	.47	.53	.61	-.60	.18	.57
ATM	2	3	5	7	9	10

Site 23 Eriophorum

3	.82					
5	.84	.95				
7	-.21	.25	.22			
9	.46	.61	.61	.26		
10	.84	.81	.83	.13	.55	
11	.80	.53	.55	-.59	.28	.76
ATM	2	3	5	7	9	10

Site 4 exposed peat surface

3	.97					
5	.93	.97				
7	-.09	.03	.17			
9	.61	.61	.67	.09		
10	.80	.81	.85	.01	.76	
11	.74	.72	.72	-.08	.65	.84
ATM	2	3	5	7	9	10

Site 5 partly vegetated peat surface

3	.90					
5	.71	.85				
7	-.71	-.47	-.20			
9	.47	.53	.58	-.17		
10	.84	.77	.71	-.70	.56	
11	.76	.58	.34	-.86	.31	.78
ATM	2	3	5	7	9	10

Site 6 partly vegetated peat surface

3	.76					
5	-.34	.64				
7	-.85	-.42	-.03			
9	.38	.44	.40	.27		
10	.85	.63	.42	-.84	.47	
11	.89	.60	.19	-.90	.35	.85
ATM	2	3	5	7	9	10

Site 9 young heather, incomplete cover

3	.88					
5	.82	.93				
7	-.03	.26	.42			
9	.54	.58	.55	.12		
10	.74	.61	.54	-.32	.58	
11	.22	-.04	-.09	-.63	.10	.52
ATM	2	3	5	7	9	10

Site 10 young heather, complete cover

3	.72					
5	.42	.68				
7	-.36	.10	.53			
9	.40	.34	.08	.23		
10	.69	.45	.02	-.63	.54	
11	.42	.12	-.31	-.74	.35	.70
ATM	2	3	5	7	9	10

Site 12 young heather, complete cover

3	.80					
5	.86	.90				
7	.59	.73	.78			
9	.24	.26	.28	.23		
10	.43	.40	.41	.12	.15	
11	-.41	-.51	-.52	-.74	-.12	.04
ATM	2	3	5	7	9	10

Site 14 mature heather

3	.79					
5	.77	.85				
7	.09	.23	.48			
9	.30	.34	.33	.12		
10	.63	.70	.61	-.05	.30	
11	.40	.44	.25	-.45	.19	.58
ATM	2	3	5	7	9	10

Site 17 over-age heather

3	.52					
5	.60	.80				
7	.22	.56	.67			
9	.16	.29	.24	.20		
10	.31	.44	.39	.14	.23	
11	.13	-.07	-.08	-.41	.01	.22
ATM	2	3	5	7	9	10

Table 5.9 Inter-band correlations at selected test sites

related to the thermal band, which is negatively related to the near-IR. The strong and persistent correlations between the visible bands are expected as reflectance throughout the visible spectrum is subject to the same basic controls. Similarly the negative relationship between the visible and the near-IR response has been reported extensively in the literature (see chapters 2 and 4). The major cause of spectral variation across the full image is the amount and type of vegetation present, to which, as shown in section 5.4, all wavebands are sensitive to some degree. Inter-band correlations are therefore expected to remain high at test sites which contain both vegetated and exposed surfaces, but fall for areas of uniform established cover where there is little diversity in vegetation amount or type.

The correlation matrices for the exposed peat and partially vegetated surfaces have a similar basic structure to the matrix for the whole scene, with slight variations from site to site. There is some degree of positive correlation between two or three of the visible bands in all cases, and one or all of these are positively related to the mid-IR. There is positive correlation between the mid-IR and the thermal IR, and the longer wavelengths are negatively related to the near-IR.

The relationships between bands are generally weaker in the areas with a full cover of young heather. The negative relationship between the broad visible/mid-IR group and the near-IR is present but in a reduced form and in one case the overall picture is reversed and the near-IR is positively related to the visible bands. Wardley and Milton (1985) found that this relationship persisted over a range of heathland types and that the mid-IR and the visible bands were not strongly correlated. In the mature and over-age heather stands all correlations are further reduced and only the three visible bands are connected. In the sedges site the pattern of a group of closely related visible and mid-IR bands reoccurs although this group has no relation to the near IR. There are no significant correlations in the bracken stands apart from those between the visible bands.

In summary the correlation matrices show that although some interband correlations are common to a number of sites and classes, a slightly different group of wavebands is need to characterise the response of each vegetation type in the ATM bands. Previous work (eg Townshend, 1984), has suggested that high correlations and therefore apparent redundancy between wavebands should make it possible to summarise the discriminatory information in the ATM data by using one band from each of the visible, near-IR, mid-IR and thermal IR regions. These data show however that each ATM band is independently important in characterising the response of one or more of the test sites. The overall feature space for the whole image cannot be reduced uniformly without losing potentially useful descriptive and discriminatory information for one or more sites.

The principal components of each training set were calculated to examine the nature and dominance of the spectral dimensions in the data in more detail.

The principal components of a data set are a set of axes which redefine the total variance of the data such that the first axis or component accounts for as much of the total variance as possible. Subsequent components account for as much of the remaining variance as possible whilst being uncorrelated with the first component and with each other (Daultrey, 1976). The maximum number of components extracted is equal to the number of original variables and each component is weighted according to the amount of variance it describes. Each component is a linear combination of the original variables. In practice the majority of the variance is summarised in the first few axes and the lower order components account for such small amounts of variance that they are often discarded although they may contain useful and unique information.

Principal components analysis (PCA) therefore reduces multiple, correlated axes to a smaller number of uncorrelated axes. In analysis of remote sensing data PCA is most often used to define the "intrinsic dimensionality" of a data set or as a data enhancement technique whereby the components are used as new variables for display or classification. The tasseled cap transform of Kauth and Thomas (1976), and its extension to TM data by Crist and Cicone (1984) are based on PCA (Crist and Kauth, 1986). In these cases specific interpretations are given to each component and the transformed feature space is a more direct match to that of vegetation and environmental variables.

PCA is used here to examine the distribution and sources of variance in the data set (figure 5.13). The PCA was performed through the MIDAS statistical package, using the correlation matrix as the basic input (Singh and Harrison, 1985). The analysis produced eigenvalues, eigenvectors, and, after further calculation, component loadings. The eigenvalue is the proportion of the total variance in the data which is accounted for by that component, and the eigenvectors are the weightings of the original axes onto the new components. The loadings are derived from the eigenvectors and eigenvalues and are the correlation coefficients between the component and the original variable or waveband. When squared, each component loading is therefore the proportion of variance in the component which is accounted for by variance in the original waveband. If components of common identity and dominance can be extracted from all the test sites the full spectral data set can be reduced in an identical way for all test sites.

Table 5.10 lists the eigenvalues for a selection of the vegetation classes used in this analysis. In most cases three or four uncorrelated axes account for over 95% of the variance in the seven band data set. However the amount of variance expressed by each component is not constant even for stands from the same broad vegetation class. Table 5.11 lists the loadings of each waveband on each component which accounts for 5% or more of the original variance.

For all the sites the first component is dominated by reflectance in the

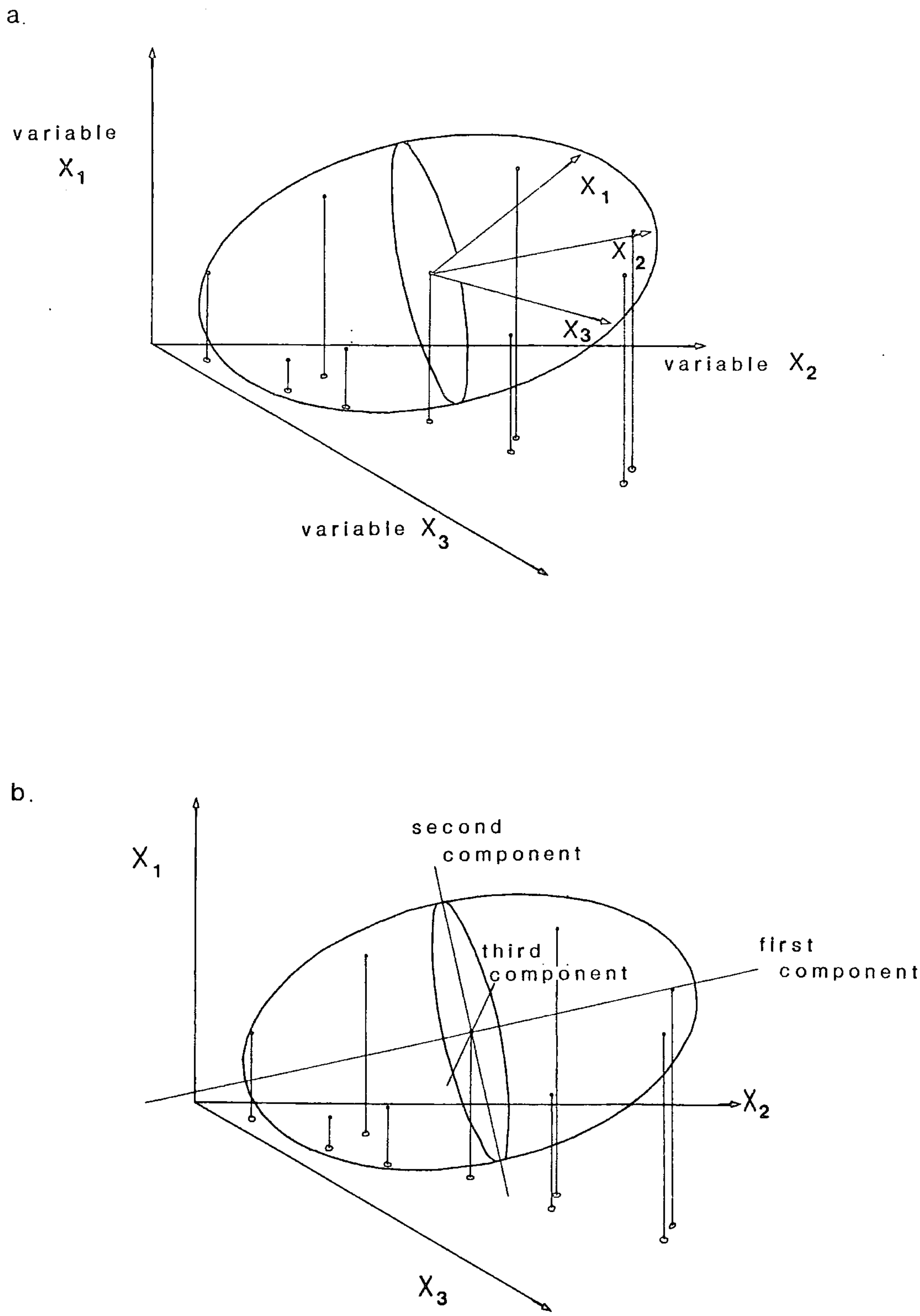


Figure 5.14 Definition of the principal components of a distribution in relation to the original variables. The first component defines the major axis of variation in the data, the second and third describe progressively smaller independent sources of variance. After Daultrey, (1976).

Site	Component 1	2	3	4	5	6	7
Whole scene	67.72	21.85	6.30	1.67	n/a	n/a	n/a
Bracken	53.44	18.34	12.91	6.25	3.75	3.56	1.75
Sedges	63.92	23.67	7.25	2.30	1.30	0.87	0.69
Exposed peat surface	70.10	15.08	7.96	4.36	1.84	0.42	0.24
Partially vegetated surface (site 5)	66.72	18.99	8.03	2.80	1.81	0.94	0.71
Partially vegetated surface (site 6)	64.64	18.93	9.43	3.99	1.30	1.14	0.57
Young heather (site 9)	54.15	28.29	8.27	5.09	2.38	0.99	0.83
Young heather (site 10)	47.37	31.06	10.26	4.03	2.90	2.75	1.63
Mature heather (site 14)	52.06	22.61	11.83	5.45	4.35	2.29	1.42
Over-age heather (site 17)	43.93	21.35	13.08	8.68	6.87	4.04	2.05

Table 5.10 Eigenvalues for selected test sites; results of principal components analysis on 7 ATM bands. See text for explanation.

Site 1 bracken

Compt.	1	2	3	4
ATM 2	.81	.35	.24	.12
3	.86	.31	.24	.12
5	.92	.15	.10	-.04
7	-.39	.86	.07	-.13
9	.38	.29	-.86	.18
10	.79	-.45	-.19	-.56
11	.78	-.45	.02	.20

Site 23 Eriophorum

Compt.	1	2	3
ATM 2	.93	-.19	.13
3	.92	.29	.18
5	.93	.26	.17
7	-.05	.97	.17
9	.65	.42	-.63
10	.94	-.10	-.01
11	.77	-.59	-.04

Site 4 exposed peat

Compt.	1	2	3
ATM 2	.94	-.13	.28
3	.94	.01	.30
5	.96	.15	.21
7	.03	.99	.02
9	.79	.10	-.52
10	.93	-.02	-.17
11	.86	-.14	-.21

Site 5 part exposed

Compt.	1	2	3
ATM 2	.95	-.06	.17
3	.89	.27	.27
5	.76	.55	.25
7	-.73	.64	.08
9	.58	.53	-.61
10	.94	-.05	-.08
11	.80	-.51	-.13

Site 6 part exposed

Compt.	1	2	3
ATM 2	.84	-.34	.24
3	.63	.69	.09
5	.66	.93	.10
7	-.64	.68	-.20
9	.63	.06	-.77
10	.92	-.11	-.13
11	.74	-.50	.11

Site 9 young heather

Compt.	1	2	3	4
ATM 2	.93	-.10	-.26	.08
3	.93	.23	-.17	.06
5	.90	.34	-.09	-.12
7	.13	.91	.11	-.36
9	.73	.01	.67	.09
10	.81	-.47	.03	.06
11	.21	-.87	.02	.44

Site 10 young heather

Compt.	1	2	3
ATM 2	.84	.34	.24
3	.63	.69	.09
5	.16	.93	.10
7	-.64	.68	-.20
9	.63	.06	-.77
10	.92	-.11	.13
11	.74	-.50	.11

Site 14 mature heather

Compt.	1	2	3	4
ATM 2	.87	.00	.15	-.42
3	.93	.09	.12	-.03
5	.89	.36	.13	.00
7	.19	.92	.03	.27
9	.47	.08	-.88	-.05
10	.82	-.26	.07	.29
11	.55	-.72	-.01	.23

Site 17 over-age heather

Compt.	1	2	3	4	5
ATM 2	.68	.30	.32	.48	-.32
3	.90	.02	.04	-.05	.13
5	.93	-.06	.13	.03	.16
7	.73	-.53	-.01	-.13	.24
9	.38	.17	-.88	.21	-.03
10	.51	.60	-.04	-.55	-.27
11	-.17	.86	.09	.09	.46

Table 5.11 Component loadings for selected sites. See text for explanation

visible wavebands although the three visible bands contribute in different proportions at each site. The IR bands contribute to the first component where they are correlated with the visible bands. Thus ATM 10 has a generally high loading on the first component. At sites 5 and 6 all bands load highly on the first component and this is expected from the correlation matrices for these sites. At sites 12 and 10 ATM 5 varies independently to the other visible bands (table 5.9), and this variance is the basis for the second component. For these sites therefore the two major axes of variation are both in the visible spectrum. More commonly, the second and subsequent components are dominated by the near and mid- or thermal IR.

In the established heather canopies (classes 14 - 21) the second component describes the difference between the thermal IR and the near-IR response. The thermal IR has a higher weighting for the over-age heather stands and the heather/sedge mix. The noisy mid-IR band ATM 9 dominates the 3rd or 4th component for all test sites.

It is clear from the PCA that the spectral description of each test site can be reduced in most cases to three or four important dimensions. As suggested from the correlation matrix, the bracken stand is an exception to this rule. The distribution of variance over the components is not however the same for each canopy. The loadings of the wavebands onto the new components is also different for each class. There is some support for the idea that a band from each of the visible, near-IR and mid- or thermal IR regions will contain most of the independent information on vegetation status, but this would omit important sources of variation at a number of sites. In practical terms this means that selecting and processing data to produce thematic maps of the moorland vegetation must take detailed account of the vegetation types to be separated.

The correlation matrices and PCA confirm and extend the results of section 5.4. The number and identity of the wavebands needed to describe all sources of variation in the spectral response of a canopy is specific to that canopy although some generalisations can be made. This suggests that there will be a similar variety and specificity in the spectral information needed to isolate each canopy.

5.6 Transformed Divergence

The discriminating ability of different waveband combinations is examined further by calculating the Transformed Divergence (TD) for all pairs of test sites for all combinations of wavebands. This allows a clear test of the hypothesis proposed in section 5.1, that a set of targets will be best separated by a combination of wavebands peculiar in number and identity to that set of targets. This in turn examines the broader question of the importance of acquiring and retaining specific spectral information in order to delimit moorland targets.

As in section 5.4 the separation of the test sites was examined at two levels. The distinctions between the broad classes of bracken, exposed surfaces, heathers and sedges were examined first.

The results of section 5.4 showed that the bracken stand can be isolated from all other surfaces in ATM 11 and ATM 7 but is confused with elements of the heather class in the visible and the mid-IR bands. Several two band combinations distinguish bracken completely (TD=2000) from the exposed peat surface. The best results occur where different parts of the spectrum are combined, but TD > 1985 for all combinations except ATM 9 with ATM 2, ATM 3 or ATM 5. Bracken is similarly well separated from the partially vegetated surface. In this case the two band combinations where TD=2000 all contain ATM 10 or ATM 11, which is expected from section 5.4. The lowest separations are for ATM 9 with ATM 3 or ATM 5 (TD=1864 and TD=1943 respectively), and the combinations of two visible bands, where TD ranges from 1910 to 1921.

The bracken stand is also clearly separated from the mature heather site (TD=2000) by 2 wavebands although compared to its separation from the exposed sites the TD values are spread over a much greater range (table 5.12). The combination of ATM 3,ATM 5; or a visible band, particularly ATM 3, with any of the IR bands gives the best separations. As might be expected from the results of section 5.4, the mid-IR and the thermal IR together give a poor discrimination of these canopies.

Overall, the ATM 3,ATM 5 subset gives the best discrimination between the bracken and both the over-age and the young heather canopies (TD=1952 at site 19 and 1905 at site 9 respectively in the worst case - see table 5.12 for examples). The addition of any of the IR bands increases the maximum TD values only slightly to a worst case of 1989 and 1978 for the over-age and the young heather canopies respectively. As noted in section 5.5, bands ATM 3 and ATM 5 are highly correlated at all the heather sites but are virtually independent axes of variation in the bracken stands, where ATM 7 is a source of further independent spectral information. ATM 10 and ATM 11 are related to each other but are independent of the reflective bands at the bracken site.

It is clear from table 5.12 that ATM 5 is important in the separation of the bracken and the sedge classes, and this was also suggested in section 5.4. There is a wide spread of TD values; ATM 3,ATM 5 and ATM 2,ATM 5 give the best results (TD=1987 and TD=1966 respectively) although ATM 2,ATM 3 has one of the lowest values (TD=1056). Combinations without ATM 5 fare badly at all levels although the effect is not as dramatic as for the heather classes and the addition of an independent third band (near IR) or the correlated mid-IR to these combinations makes only a marginal difference to the TD values.

These results show that the bracken stands can be isolated from any other site with a minimum of spectral information if this information is selected carefully. This is particularly true for the separation of bracken from the other vegetated sites. ATM 3 and ATM 5 give consistently good discrimination between bracken and the other vegetated areas although they are relatively poor at recognising bracken from the exposed surfaces.

Table 5.12 Transformed Divergence (TD) values: spectral separation of bracken and selected test sites, September 1983 ATM data. Each table shows the five highest and the five lowest results.

Site 1 Site 9

TD	ATM 2	3	5	7	9	10	11
1905		X	X				
1844		X				X	
1806	X					X	
1762						X	X
1745			X			X	
1034	X			X			
1022		X		X			
738		X			X		
722	X	X					
496	X				X		

Site 1 Site 10

TD	ATM 2	3	5	7	9	10	11
1994		X					X
1986	X						X
1976		X	X				
1948		X					
1916				X			X
1622	X	X					
1225	X				X		
1143			X			X	
769					X	X	
86			X		X		

Site 1 Site 12

TD	ATM 2	3	5	7	9	10	11
2000		X	X				
1918		X					X
1835		X		X			
1827		X				X	
1777	X	X					
850				X		X	
769				X	X		
254			X			X	
182					X	X	
167					X		

Site 1 Site 14

TD	ATM 2	3	5	7	9	10	11
2000		X					
		X	X				
		X		X			
1999	X			X			
		X				X	
1648						X	
1222					X		X
958			X		X		
857			X			X	
680					X	X	

Site 1 Site 17

TD	ATM 2	3	5	7	9	10	11
1989			X	X			
1979		X	X				
1947				X		X	
1945		X				X	
1929		X					X
1525					X	X	
1224		X			X		
911	X	X					
706		X			X		
626			X		X		

Site 1 Site 18

TD	ATM 2	3	5	7	9	10	11
1999		X	X				
1939		X					X
1938			X	X			
1936		X				X	
1779		X		X			
1338	X		X				
1213		X	X				
1104					X	X	
545	X				X		
264			X		X		

Site 1 Site 19

TD	ATM 2	3	5	7	9	10	11
1952		X	X				
1810			X	X			
1747						X	X
1733		X				X	
1540				X		X	
878			X		X		
872	X						X
755	X	X					
577		X			X		
117	X				X		

Site 1 Site 23

TD	ATM 2	3	5	7	9	10	11
1987		X	X				
1966	X		X				
1896			X		X		
1875			X	X			
1874			X			X	
1512				X			X
1413		X					X
1080		X		X			
1056	X	X					
586	X			X			

Other wavebands return high TD values for the separation of bracken from specific sites, for example the near-IR at the exposed peat surface and also at the heather/Eriophorum mix; and ATM 11 or ATM 10 for the regenerating surfaces. The combination of ATM 5,ATM 7 has good discriminating power between the bracken and the over-age stands but gives surprisingly poor results at all other sites. These results therefore confirm the proposals of sections 5.4 and 5.5 that pairs and groups of vegetation types are best separated by specific combinations of wavebands.

When sufficient spectral information is included the exposed surfaces and the heather classes can be separated from the sedges stand with TD values similar to their separation from the bracken site (table 5.13).

Two band combinations which include the near-IR separate the sedges from the exposed peat surfaces, although the thermal IR is an acceptable alternative, and the mid- or thermal IR are preferred for the separation of the sedges from the partially vegetated surfaces. These results can be predicted from the figures of section 5.4. In both cases there is a wide range of TD values across the possible two band combinations (table 5.13).

As in the case of bracken, ATM 3 is the most important band in the isolation of the sedges from the young heather classes. The TD values for the discrimination between the sedges and sites 10 and 12 is >1970 for all 2 band combinations which include ATM 3 (table 5.13). Site 9, where the young growth of heather is not yet complete, is consistently confused with the sedge class although the two are very different on the ground. The maximum separation between site 9 and the sedges is 1671 when all 7 bands are included. The low separation of these sites is due in part to the high variance in response for site 9. As noted in section 5.1 this is not necessarily a poor result in management terms.

ATM 3 is also important in the separation of the sedges from the mature and the over-age heather stands although the degree to which this distinction is made varies considerably from one heather canopy to another (table 5.13). For three of the four over-age canopies sampled, ATM 3 is

Table 5.13 TD values: spectral separation of sedges and selected test sites, September 1983 ATM data.

Site 23 Site 4

TD	ATM 2	3	5	7	9	10	11
2000	X			X			
		X		X			
			X	X			
				X	X		
				X		X	
				X			X
1368	X						
1240	X					X	
686		X	X				
335			X		X		
127		X	X				

Site 23 Site 5

TD	ATM 2	3	5	7	9	10	11
2000			X			X	
1999		X				X	
1987			X				X
	X						X
1985		X					X
1737	X		X				
904	X				X		
413			X		X		
284		X			X		
252		X	X				

Site 23 Site 9

TD	ATM 2	3	5	7	9	10	11
993		X				X	
1307		X		X			X
1474		X		X		X	X
1565	X	X		X		X	X
1632	X	X		X	X	X	X
1671	X	X	X	X	X	X	X

Site 23 Site 10

TD	ATM 2	3	5	7	9	10	11
1992		X		X			
1990		X					X
1985		X					
1981	X	X					
1970		X					
1603						X	X
1596					X		X
1561	X				X		
1489	X					X	
1299					X	X	

Site 23 Site 12

TD	ATM 2	3	5	7	9	10	11
2000		X					X
		X	X				
1999		X		X			
1996	X	X					
		X			X		
1788				X			X
1748				X	X		
1705			X	X			
1618	X		X				
1601	X			X			

Site 23 Site 14

TD	ATM 2	3	5	7	9	10	11
2000	All combinations with ATM 3						
1984					X	X	
1983	X				X		
1972						X	X
1967	X						X
1904					X		X

Table 5.13 cont.

Site 23 Site 17

TD	ATM	2	3	5	7	9	10	11
1965			x					x
1947			x		x			
1945			x				x	
1936		x	x					
			x	x				
1617		x						x
1556		x					x	
1537						x		x
1511						x	x	
1391							x	x

Site 23 Site 18

TD	ATM	2	3	5	7	9	10	11
1996			x	x				
1978			x		x			
1977			x					x
1975		x	x					
1973			x				x	
1474		x						x
1447						x	x	
1388		x					x	
1344						x		x
1016							x	x

Site 23 Site 19

TD	ATM	2	3	5	7	9	10	11
1663					x			x
1523						x		x
1351			x	x				
1342		x	x					
1323			x			x		
971				x	x			
963		x		x				
917				x			x	
840		x			x			
645		x					x	

Site 23 Site 21

TD	ATM	2	3	5	7	9	10	11
1997			x	x				
1990			x				x	
1984		x	x					
1981			x		x			
1977			x					x
1230		x					x	
1123					x	x		
993						x	x	
804						x		x
698							x	x

present in the two band combinations which hold the most discriminatory information and the TD falls dramatically when ATM 3 is omitted. ATM 11 contains independent spectral information on the over-age stands which is also important in their discrimination from the sedges, especially at site 19.

The exposed peat surface (site 4) and the regenerating site (site 5) are both separated from the mature heather canopy (TD=2000) by virtually any two band combination, and this might be expected from the distributions described in section 5.4. The choice of wavebands is more critical if the boundaries between the exposed or partially exposed areas and the young heathers are to be recognised. The ranking of the partially vegetated sites (sites 5-8) by their spectral response corresponds roughly to a ranking by proportion of vegetation cover, and the sites overlap to span the difference in reflectance between the exposed peat surfaces and the sites with a full cover. In ecological terms sites 9, 10 and 12 carry on from sites 5 to 8 as the next stages in the continuum in development of the heather canopy. In management terms however it is desirable to split the two groups, as the partially exposed surfaces still carry a considerable risk of erosion.

The 2 band combinations which best separate the discontinuous cover of site 9 from the exposed and the partially exposed peat surfaces contain ATM 11 and ATM 7 respectively. There is considerable variation in the amount of discriminatory information in different pairs of wavebands (table 5.14). ATM 7,ATM 11 however gives relatively poor results when used to separate the young heather of site 10 from the exposed and the partly vegetated site (table 5.14), and combinations with ATM 3 are the best discriminators of these sites. Site 12 has a response closer to that of the mature heather canopy and it is separated from the exposed surfaces in virtually any two bands. The exposed surfaces are similarly well separated from the over-age canopies.

Table 5.14 TD values: spectral separation of exposed and partially exposed sites and young heather canopies, September 1983 ATM data.

Site 4 Site 9

TD	ATM 2	3	5	7	9	10	11
1994	X			X			
1992		X		X			
1989			X	X			
1988				X		X	
				X			X
1042	X				X		
1032					X	X	
540		X	X				
494			X		X		
395		X			X		

Site 4 Site 10

TD	ATM 2	3	5	7	9	10	11
1997			X	X			
1995		X		X			
1985	X			X			
1984	X	X					
1972	X		X				
1841		X			X		
1829				X	X		
1812				X			X
1610					X	X	
1350					X		X

Site 4 Site 12

TD	ATM	3	5	7	9	10	11
2000	All combinations except those below						
1995	X		X				
1988	X	X					
1985	X				X		
1775		X			X		
			X		X		

Site 5 Site 9

TD	ATM 2	3	5	7	9	10	11
1911						X	X
1903					X		X
1891		X					X
1881			X				X
				X			X
1259	X				X		
1219	X		X				
1185		X			X		
1169			X		X		
754		X	X				

Site 5 Site 10

TD	ATM 2	3	5	7	9	10	11
1992	X	X					
1991		X		X			
1987		X			X		
1986		X				X	
1984				X		X	
1947	X						X
1896			X		X		
1854					X		X
1817				X			X
1694				X	X		

Site 5 Site 12

TD	ATM 2	3	5	7	9	10	11
2000	All combinations except those below						
1999			X	X			
1998			X		X		
1983				X	X		

These results show that for most of the sample sites, the sedges, the bracken, the heather stands and the exposed surfaces can be separated from each other with a minimum of spectral information. In most cases there are a number of waveband combinations which give an acceptable separation. For other canopies however, specific wavebands are required and only limited substitution is possible.

The second level of discrimination that is needed for management of the moorland community is between the stages of heather growth described in chapter 3. The training sets examined here are from a mature canopy (site 14), a series of overage canopies (sites 17-21), the three stands of young heather (sites 9,10,12), and a number of sites with varying amounts of patchy pioneer growth (sites 5-8) discussed above (table 5.2).

The separation between the elements of the heather class, particularly the established canopies is expected to be lower than that of the major cover types. Compared to the major cover types the elements of the heather class are ecologically similar and they have a substantially similar spectral response. The greatest similarities are expected to occur within the young stands and within the over-age stands. In fact sites 10 and 12, both with a full young canopy, have a reasonable separation from each other if ATM 11 or, with rather less consistent success, ATM 7, is included. They are however confused with each other in all other two band combinations (table 5.15). This might be expected from the results of section 5.4. Site 12 is distinct from the more patchy cover of site 9 if ATM 3 or ATM 7 is present; sites 9 and 10 are less clearly separable with this amount of spectral information, although their separation increases as spectral information is added. The maximum divergence of these two classes, when all 7 bands are included, is only however 1896.

The reflectance characteristics of the four over-age stands sampled are broadly similar, although the analyses of section 5.4 show that they occupy slightly different parts of the overall distribution in each waveband.

Table 5.15 TD values: spectral separation of young heather canopies from

Site 10 Site 12

TD	ATM 2	3	5	7	9	10	11
1824						X	X
1802		X					X
1793			X				X
1767				X			X
1740	X						X
297	X				X		
270	X	X					
230			X		X		
225		X	X				
184		X			X		

Site 9 Site 12

TD	ATM 2	3	5	7	9	10	11
1968		X		X			
1967		X					X
1956		X				X	
1954						X	X
1938					X	X	
				X		X	
1283				X			X
1248	X				X		
1151	X		X				
1011			X		X		
950				X	X		

Site 9 Site 10

TD	ATM 2	3	5	7	9	10	11
1620		X		X			
1588		X					X
1549	X	X					
1543		X				X	
1542	X			X			
929			X				X
925				X	X		
755				X			X
559					X		X
414					X		X

Table 5.16 TD values: spectral separation of over-aged heather canopies from each other in combinations of six wavebands, September 1983 ATM data.

Site 17 Site 18

TD	ATM 2	3	5	7	9	10	11
1325		X	X	X	X	X	X
799	X		X	X	X	X	X
959	X	X		X	X	X	X
1274	X	X	X		X	X	X
1327	X	X	X	X		X	X
1309	X	X	X	X	X		X
1239	X	X	X	X	X	X	

Site 17 Site 19

TD	ATM 2	3	5	7	9	10	11
1273		X	X	X	X	X	X
1169	X		X	X	X	X	X
1322	X	X		X	X	X	X
1385	X	X	X		X	X	X
1394	X	X	X	X		X	X
1400	X	X	X	X	X		X
1177	X	X	X	X	X	X	

Site 17 Site 21

TD	ATM 2	3	5	7	9	10	11
1482		X	X	X	X	X	X
1187	X		X	X	X	X	X
1312	X	X		X	X	X	X
1558	X	X	X		X	X	X
1565	X	X	X	X		X	X
1556	X	X	X	X	X		X
1402	X	X	X	X	X	X	

Site 18 Site 19

TD	ATM 2	3	5	7	9	10	11
1482		X	X	X	X	X	X
1187	X		X	X	X	X	X
1312	X	X		X	X	X	X
1558	X	X	X		X	X	X
1565	X	X	X	X		X	X
1556	X	X	X	X	X		X
1402	X	X	X	X	X	X	

Site 18 Site 21

TD	ATM 2	3	5	7	9	10	11
787		X	X	X	X	X	X
837	X		X	X	X	X	X
734	X	X		X	X	X	X
928	X	X	X		X	X	X
830	X	X	X	X		X	X
866	X	X	X	X	X		X
929	X	X	X	X	X	X	

Site 19 Site 21

TD	ATM 2	3	5	7	9	10	11
1624		X	X	X	X	X	X
1461	X		X	X	X	X	X
1655	X	X		X	X	X	X
1751	X	X	X		X	X	X
1711	X	X	X	X		X	X
1748	X	X	X	X	X		X
1694	X	X	X	X	X	X	X

Table 5.16 shows their separation from each other in the six and seven band combinations. Sites 18 and 20 clearly have very similar reflectance characteristics and cannot be separated in these data. As predicted from the Dnorm values, ATM 3 is important in making some distinction between the remaining classes, ATM 5 is also important for the identification of site 18 from sites 17 and 19, and ATM 11 is as important as ATM 3 in the recognition of site 19 from site 17. Compared to the differences in response between the young heather stands the spectral separation between the samples of the over-age heather is low.

These figures show that ecologically similar components of the moorland community can be separated from each other by their spectral response, and in some cases, with greater clarity than is possible for completely different cover types. However tables 5.15 and 5.16 show that only certain wavebands are able to make these distinctions and this is true even in the presence of highly correlated wavebands. In the separation of site 10 and site 9 for example, the combination of ATM 2,ATM 5,ATM 11 returns a TD value of 929. If ATM 3 is substituted for ATM 2 the TD value rises to 1647 although the correlation between ATM 2 and ATM 3 is 0.72 at site 9 and 0.88 at site 10.

The over-age stands are most similar in vegetation terms to the mature heather canopy and the area where heather is mixed with Eriophorum. These two stands are ecologically similar and are differentiated primarily by the presence of a wetter substrate and clumps of Eriophorum in the latter. The two stands are also spectrally similar. Their strongest separation is in the visible and the mid-IR bands, although the maximum TD (7 bands) is only 1627.

As suggested in section 5.4 each of the over-age stands is clearly separated from the mature heather and the heather/Eriophorum canopies in the visible and the mid-IR wavebands. The optimum combination of bands for this separation is slightly different for each of the over-age stands (table 5.17). The clear separation of the mature canopies from the

Table 5.17 TD values: spectral separation of mature heather from young and over-age canopies, September 1983 ATM data.

Site 14 Site 9

TD	ATM 2	3	5	7	9	10	11
1988		X				X	
1987		X					X
1985		X	X				
		X		X			
1983				X			
1856							
1855							
1849							
1698							
1467							

Site 14 Site 10

ATD	TM 2	3	5	7	9	10	11
1726				X			X
1711			X				X
1679		X					X
1650		X				X	
1637			X			X	
1174	X		X				
1142			X	X			
902	X				X		
850	X			X			
772				X	X		

Site 14 Site 12

TD	ATM 2	3	5	7	9	10	11
1842				X			X
1764				X		X	
1722		X		X			
1713	X			X			
1617			X	X			
1015	X				X		
998						X	X
916			X		X		
884					X		X
280					X		X

Site 14 Site 17

TD	ATM 2	3	5	7	9	10	11
1980		X				X	
1979				X		X	
1975	X					X	
1969	X	X					
1968		X				X	
1791			X		X		
1786			X				X
1779			X	X			
1726					X		
1318					X		X

Site 14 Site 18

TD	ATM 2	3	5	7	9	10	11
1898	X					X	
1850				X		X	
1835		X				X	
1803			X			X	
1705	X			X			
1482				X			X
1433			X		X		
1338			X	X			
1148				X	X		
1021					X		X

Site 14 Site 19

TD	ATM 2	3	5	7	9	10	11
1941	X			X			
1935	X	X					
1931		X		X			
1929		X					X
1928				X		X	
1756			X		X		
1721				X			X
1700				X	X		
1692					X	X	
872					X		X

over-age stands is a useful result in terms of management, but the differences in the canopy do not seem large enough to explain such a dramatic change in reflectance.

The spectral response of the young heather areas is close to that of the mature heather stand, but the two groups are separable if sufficient spectral information is included. The main difference between the areas with a full canopy of young heather (sites 10 and 12) and the mature stand is the total biomass present, as all stands are heather monocultures. The combinations of ATM 7,ATM 11; ATM 7,ATM 10,ATM 11; and ATM 5,ATM 7,ATM 10,ATM 11 give good separation of these two groups although ATM 2,ATM 5,ATM 9,ATM 10,ATM 11 is optimal in the five band combination. Table 5.17 also shows that ATM 7 is particularly important in the separation of site 12 from the mature canopy, ATM 11 and ATM 10 are similarly important for site 10. These combinations are not optimal for the separation of site 9 from the mature canopy but still give acceptable results.

As noted in section 5.4, a critical confusion occurs where the spectral response of the young and regenerating heathers, particularly site 9, is inseparable from that of the over-age classes. As suggested from section 5.4 ATM 11 offers the best chance of distinguishing these canopies and this is confirmed by the results of the divergence analysis. The TD values for the discrimination of sites 17 and 9 rise from 1703 for ATM 3,ATM 11 to 1861 for the 7 band case, with the successive entry of ATM 7 (1788), ATM 10 (1834), ATM 2 (1852) and ATM 5 (1859). ATM 3 and ATM 11 are clearly critical. When they are removed in turn from the 7 band combination TD falls to 1801 and 1737 respectively.

The thermal band is also important in the isolation of site 17 from site 10, with a maximum 2 band separation of 1939 (ATM 2,ATM 11), and a 6 band maximum of 1989. TD falls to 1898 if ATM 11 is omitted from the six band combination. The ATM 3,ATM 7 combination is important in the separation of sites 17 and 12 and the absolute levels are similar to those for site 9.

As expected from the similarities between some of the samples from the over-age canopies these patterns are repeated for sites 18-21. The 2 band combinations which optimally separate site 9 from all other vegetated stands (ATM 3, ATM 5) is also a clear optimum for the separation of site 9 from the over-age heather sites 18 and 20. The 6 band combinations (table 5.18) show that ATM 3 is important for the separation of all elements of the over-age class from this site of young heather but unimportant for site 10. Similarly, ATM 11 is important for the isolation of sites 10 and 9 from some over-age stands but is less critical for site 12.

All the over-age stands carry some risk of fire and the possibility of severe erosion. It is therefore important that they are all picked up in a classification. To satisfy this criterion the three band combinations ATM 3,ATM 5,ATM 11; ATM 3,ATM 7,ATM 10 and ATM 2,ATM 10,ATM 11 (table 5.19) would need to be run as separate classifications as each fails to discriminate between certain pairs of classes and there is no band common to all groups.

5.7 Conclusion

The results presented here show that the original hypothesis, that the discriminatory information in an image increases in proportion to the number of independent wavebands, is not supported for most of the moorland sites. The revised hypothesis, that a set of targets will be best separated by a combination of wavebands peculiar in number and identity to that set or subset of targets, is however generally supported. The precise combination of bands used is important in the separation of classes at all levels, and in a number of cases the presence of one particular band appears to be critical. Where this is not the case, the addition of new spectral information does increase the separability of the samples. The optimum combinations are not necessarily made up of independent bands or spectral regions, and classes which show high inter-band correlations in their spectral response are as clearly separated from the remaining samples as those which show very little inter-band correlation.

Site 9	Site 17	Site 18	Site 19	Site 20
minus				
ATM 2	1843	1876	1495	1926
ATM 3	1801	1459	1429	1398
ATM 5	1854	1754	1562	1861
ATM 7	1822	1869	1569	1896
ATM 9	1859	1890	1596	1919
ATM 10	1825	1875	1554	1916
ATM 11	1737	1867	1148	1897

Site 10	Site 17	Site 18	Site 19	Site 20
minus				
ATM 2	1969	1438	1939	1757
ATM 3	1987	1771	1981	1780
ATM 5	1968	1687	1975	1809
ATM 7	1979	1716	1974	1726
ATM 9	1989	1794	1989	1822
ATM 10	1980	1667	1985	1663
ATM 11	1898	1533	1937	1705

Site 12	Site 17	Site 18	Site 19	Site 20
minus				
ATM 2	1917	1656	1861	1886
ATM 3	1824	1663	1611	1923
ATM 5	1904	1643	1913	1877
ATM 7	1866	1501	1813	1863
ATM 9	1908	1642	1863	1872
ATM 10	1831	1503	1799	1767
ATM 11	1916	1652	1814	1908

Table 5.18 TD values: separation of young and over-age heather stands in 6 band combinatins

ATM 3, ATM 5, ATM 11

Sites	TD	Sites	TD	Sites	TD
9 : 17	1717	10 : 17	1925	12 : 17	1585
9 : 18	1815	10 : 18	938	12 : 18	916
9 : 19	1326	10 : 19	1864	12 : 19	1559

ATM 3, ATM 7, ATM 10

Sites	TD	Sites	TD	Sites	TD
9 : 17	1719	10 : 17	1959	12 : 17	1673
9 : 18	1268	10 : 18	1381	12 : 18	1434
9 : 19	1309	10 : 19	1918	12 : 19	1973

ATM 2, ATM 10, ATM 11

Sites	TD	Sites	TD	Sites	TD
9 : 17	1680	10 : 17	1571	12 : 17	1856
9 : 18	1665	10 : 18	723	12 : 18	1542
9 : 19	863	10 : 19	1570	12 : 19	1641

Table 5.19 TD values: spectral separation of young and over-age heather stands in three band combinations

The results imply that the spectral dimensions of the full data set cannot be reduced uniformly without losing valuable descriptive and discriminatory information for some canopies. Further, the intrinsic dimensionality of the data is not a particularly good indicator of the number and identity of wavebands that will be needed to separate targets. It was shown in the ground radiometry data however that the discriminating power of the visible and the near-IR wavebands may change over the year. It is therefore possible that the dimensionality of the data, and the combinations of wavebands which best separate a set of canopies, will change over the growing season. This is examined further in the next chapter.

Chapter 6: Analysis of multispectral scanner data from different dates, the importance of temporal resolution.

6.1 Introduction

The analysis and discussion of chapter 5 has shown that most of the different components of the moorland community can be isolated and recognised by their spectral response. The discriminating information of the full data set can, for almost any pair or group of canopies, be retained in a reduced number of wavebands. The size and content of these subsets of bands is specific to the canopies to be separated, although a number of canopies show similar patterns of separation and some subsets of bands discriminate clearly between diverse pairs and groups of cover types. In most cases however, a subset of wavebands will separate pairs or groups of classes which are inseparable in other spectral combinations. The diverse make-up of the optimal combinations shows that each of the ATM bands is important in identifying one or more elements of the moorland community.

As discussed in chapter 2 and subsequent chapters, the amount of energy radiated in each part of the spectrum is directly controlled by one or more physiological or structural features of the plant or canopy. The spectral separation of different canopies therefore depends on their separation when described by these controlling features. The parameters of each controlling feature vary with plant health, maturity, stress and environment and there will be corresponding variation in the canopy's spectral response. The most regular and predictable variations in the controlling features occur over the growing season of the plant. It is clearly desirable to acquire remote sensing data at a time when any consequent changes in response have the effect of maximising the spectral separation of important vegetation classes. Temporal resolution, defined as the date of data acquisition, may therefore help to determine the efficacy of the sensor's spectral resolution and thus limit or extend the amount of information in the data.

Both the SPOT and the Landsat systems, under commercial management, have moved towards the programmed request form of data acquisition so that specific targetting for optimal temporal windows is possible. It is therefore economically sensible to establish whether acquiring data in a specific window can make a significant reduction in the number and diversity of wavebands needed to separate important elements of the target.

This chapter examines the importance of temporal resolution in recognising elements of the moorland community and, in particular, its importance relative to spectral resolution. The basic hypothesis, outlined in chapter 1, is that temporal resolution is unimportant in the moorland community, in that there is little obvious seasonality in most of the *Calluna* dominated areas. In this case data from random dates will hold equal discriminatory information. This tenet is discussed in greater detail in section 6.2. The data used are described in section 6.3.

The optimum time of year to collect data can be predicted most accurately for homogeneous targets which pass through a number of definite phases in the annual cycle. This is typical of extensive agricultural targets and considerable research work in the USA has been directed towards building "spectro-temporal profiles" for common crops (see Ajai *et al.*, 1985; Odenweller and Johnson, 1984; Badhwar, 1984). These describe the way in which the spectral response of each crop varies over time and how multi-date data can be used to identify and isolate crops which have a generally similar response. Deviations from the normal profile may also be indicative of stress or disease and the profiles can be used to identify the optimum date for acquiring single date data.

The effect of seasonal change in the more complex canopies of natural communities is less predictable. As outlined in chapter 2 a similar radiance may result from a number of plant conditions and vice versa. Thus a time-dependent change which makes two stands ecologically distinct may have the effect of bringing their spectral response closer together.

Although a number of studies have examined the importance of temporal resolution for mapping and monitoring natural habitats their conclusions are specific to certain communities and cannot be applied easily outside them. Morton (1986) suggests that spectro-temporal curves for common moorland vegetation types would facilitate the interpretation of Landsat MSS data for these areas. In the absence of such information, the importance of temporal resolution to moorland management can only be evaluated on a trial and error basis, although tentative temporal windows can be defined from knowledge of seasonal change in the plants and the environment.

This study can consider only a limited number of data sets. An alternative and fuller investigation could use data from the AVHRR sensor on the TIROS-N weather satellites, which are available for every cloud free day. Although the detail of the moorland communities cannot be distinguished in data with such a low spatial resolution (1.1km x 1.1km), a preliminary survey could be conducted for the full growing season on the premise that a high spectral contrast and variance over the moorland areas represents potentially good discriminating information.

6.2 Moorland phenology

Table 6.1 is an outline of the physiological and morphological changes that occur in the common moorland species over the growing season. Some, such as the production of new green shoots, flowering and the die back of green vegetation have a visible effect on the canopy. Others, such as the point of maximum biomass in a fully developed stand, or the high productivity associated with building reserves for periods of root growth, are less clear.

The amount of seasonal change in vegetation is different for each element of the moorland community. As noted in chapter 4, the isolation and identification of the elements of the heather class depends almost completely on their spectral characterization. The hypothesis of no change

	Calluna	Vaccinium	Eriophorum	P.aquilinum	Rainfall mm	(North Yorks Moors. ave. 1980-2)
	evergreen					
Jan			least active period	litter dominant	50.0	
Feb					45.8	
Mar		appearance of leafy shoots	growth initiated		123.7	
Apr	new short shoots appear	root development		frond emergence	31.0	
May	over-wintered shoots elongate	1st flowering	1st flowering		39.0	
Jun			maximum leaf prodn peak root prodn	full canopy developed	106.0	
Jul		2nd flowering		peak biomass	76.0	
Aug			peak biomass		96.0	
Sept	main flowering period		2nd flowering		73.2	
Oct	seed dissemination starts	root development		frond fall	93.5	
Nov	maximum litter		growth terminates		93.0	
Dec			decomposition dominant	decomposition dominant	65.7	

Table 6.1 Phenology of common moorland plants

in response over time was based on the expected response from the ericoid shrubs, which stay at least partially green throughout the year. Heather canopies at the building stage may be separated more clearly from the mature and the over-age stands in the spring period of maximum productivity, as the younger stands will have a high proportion of green shoots. The results of chapter 5 showed however that there is considerable variation in response within both the over-aged and the young heather classes in September, and the spectral effect of the different proportions of new growth is unlikely to overcome the variable level of spectral separation that this causes. Where a clear discrimination is dependent on the information in a single waveband or spectral region however, a minor change in response may have a considerable effect on spectral separation.

Some differentiation of sites on different substrates may be possible in the mid-IR bands in periods of high water deficit. Vegetation on the deep peat lens is likely to remain unstressed and the substrate will retain its dark colour. Water stress and a surface crusting may be introduced on the peaty podsols, especially where they are largely unvegetated. Such changes will have most effect on the separation between the fully vegetated and the exposed or partially exposed sites. They will however be site specific and closely controlled by immediate antecedent environmental conditions.

In general, little change is expected in the relative response of the heather canopies over time and there are unlikely to be any dramatic differences in their spectral separation. In contrast, the other major constituents of the moor, bracken and sedges, show marked changes in the canopy over time. The aerial parts of Eriophorum and other long-living perennial sedges bleach and die back over winter. The bracken canopy dies back completely to form a deep litter layer. On this basis the heather can be expected to be separated from the other two canopies most clearly when the winter die-back is complete.

The best separation of bracken and the sedges in ecological terms is in early spring, when growth has been initiated in the Eriophorum stands and the response of the bracken stands is still dominated by the litter layer. The bracken areas in particular are expected to show seasonal differences in near-IR response as the stands develop from litter layer through frond emergence to a full mature canopy. The two canopies are most likely to be spectrally confused in the least active period when both canopies have died back, or at the time of maximum leaf production. They are however well separated in all bands in the September 1983 data set and the major differences between the bracken and the sedge leaf and canopy may preclude such confusion. It seems unlikely that there will be complete separation of the major canopy types at one date and complete confusion at another.

In summary the elements of the moorland community are most distinct in ecological terms at the period of maximum spring growth, in high summer and other periods of water deficit, and in late autumn or early spring when the aerial parts of the bracken and the sedges have died back. With the qualifications of section 6.1 above, if temporal resolution is at all important in the moorland environment then data acquired in these periods are expected to give the best spectral separations between the moorland canopies. The effect of temporal resolution is expected to be greatest at the upper level of discrimination, between the sedges, bracken, heather and exposed surfaces. The date of acquisition is expected to have little effect within the heather class.

6.3 Data and Methodology

The data examined in this chapter are those described in chapter 5 and two similar data sets acquired on 24th May and 31st August 1984 as part of the Natural Environment Research Council's MSS 84 campaign (see Williams, 1984 for details of earlier, similar flights). All the data were collected with the Daedalus AADS 1268 scanner with the configuration described in chapter 2. The pixels in the May 1984 data are 4m x 3m in size. The pixels in the August 1984 data are 7m (along track) x 3m. This reduction in spatial resolution from that of the 1983 data is expected to reduce the intra-site and intra-class variation in the partially vegetated areas, as most pixels will cover a mixture of vegetated and non-vegetated ground within this IFOV. However the pixel area is still only c.1.3% and 2.3% respectively of a TM pixel, and the variation in these sites is expected to remain considerably higher than that from actual TM data.

The values recorded by the scanner were not corrected to the absolute scale of radiance because the calibration data available at the time of analysis were not reliable. A comparison of absolute digital values between the three data sets is not possible as the gain settings were different for all three flights. However the relationship between the scanner DN and radiance is linear although its precise form is different for each band and gain setting (Wilson, 1986). The measures of statistical separation described in section 5.3 and calculated from these data can therefore be compared directly within and between data sets.

In the May data the test sites were split across two flight lines. A comparison of a number of sites imaged on both flight lines showed a considerable discrepancy in DN between the two flight lines. In retrospect this is most likely to be due to the effects of different sun-sensor geometries on adjacent flight lines and limb brightening. At the time of analysis an attempt at correcting this discrepancy would introduce arbitrary error into the data. In the May data therefore test sites were compared directly only to those on the same flight line.

Because of the different spatial resolutions of the data sets and the general practical problems of co-registering airborne data no attempt was made to combine the two data sets precisely. The test sites used are, as far as possible, those used in the analysis of chapter 5. They are listed in table 6.2.

Clearly this is not the ideal data set with which to examine the effects of temporal resolution as fundamental variables such as spatial resolution, atmospheric conditions and sun-sensor geometry also vary between flights.

Site number	Description
1	Dense bracken stand
4	Peaty podsol surface, exposed by cutting and clearing heather. Very little vegetation.
5 6 8	Partially vegetated surfaces, regenerating after fire. Numbering of sites corresponds to increasing proportion of vegetation cover. The dominant vegetation is Calluna (up to 12 cm high), although Vaccinium and grasses are present. There are a large number of dead heather stems, and, where exposed, the peat has a surface crust which is light in colour.
9 10 12	Areas with complete or virtually complete cover of young vigorous heather, forming a carpet c. 15 cm high.
14	Mature heather stand, compact growth with complete canopy. Appox 22cm in height.
17 - 21	Over-age heathers 17 - 19: advanced stage of sites 14-16, uneven canopy 20 - 21: older stands, uneven gappy canopy.
22	Mixed mature/over-age Calluna and Eriophorum
23	Eriophorum dominated area, Calluna under-storey
24	New burn, blackened surface

Table 6.2 Test sites extracted from August 1984 ATM data. The site numbers correspond to those used in the Sept. 1983 data. * identifies a site not available in the 1983 data. See section 6.8 for May sites.

In the absence of better data however, comparisons of the type and amount of discriminatory information in each data set are still valid and this approach was adopted here. The details of analysis follow those of chapter 5 and examine the information in individual wavebands, the structure of the data set and the overall divisions of the feature space.

As individual wavebands or spectral regions respond to changes in the canopy in different ways the correlations and redundancy between bands may vary for data acquired at different dates. This will alter the structure and dimensionality of the feature space for individual canopies and for the community as a whole. Corresponding changes can be expected in the number and identity of wavebands needed to separate pairs and subsets of canopies within the community. Thus, if temporal resolution is important in this environment, the specific waveband combinations which best separate pairs or groups of canopies may differ in content and discriminating power from one time of year to another.

The information in the August 1984 data is compared to that of September 1983 in section 6.4 and the limited data set of the May 1984 acquisition is examined in the light of this comparison in section 6.5.

If the main hypothesis is not to be falsified there must be little difference between all data sets in the amount of discrimination between vegetation types, both in single spectral bands and the full spectral feature space. If the hypothesis is to be falsified there must be reasonable similarity between the August 1984 and the September 1983 data and a difference between these two dates and the May acquisition.

6.4 August 1984 data: discrimination in single wavebands

6.4.1 ATM 2

The full canopies are clearly divided from surfaces which are wholly or partially exposed. Within the vegetated sites the over-age heather stands have the lowest radiance and there is almost complete overlap between the three examples of this class. The mature heather, the Eriophorum stand and one site of young heather (site 12) form a second cluster with slightly higher radiance. The means of all these canopies however fall within 2 DN values and there is virtually no discrimination between them (table 6.3). The two remaining sites of young heather and the bracken stand mark the upper limit of response of the vegetated canopies. The bracken has some statistical separation from the older heather stands but in general the vegetated canopies are more clearly separated in the 1983 data in this waveband. The ordering of the heather canopies in the August data is however closer to that expected from the characteristics of the vegetation (see section 5.4)

The regenerating areas, the newly burnt surface and the exposed peat surface have a high radiance in this waveband. The peat surface is also clearly separated from all other components of this group. This distinction suggests that ATM 2 could be useful in monitoring the balance of cutting and burning in moorland management. The highest within class variances are in the partially vegetated areas and, as noted in chapter 5, there is a general decrease in radiance and increase in uniformity with the development of a full canopy. The internal variation in response at each of the regenerating sites is considerably reduced from that in the 1983 data.

Neither the Eriophorum nor the bracken sites are completely separate from all other sites in ATM 2. The response of the Eriophorum stand is virtually identical to that of the mature heather site and particularly the area of mixed Calluna and Eriophorum (table 6.3). This is in marked contrast to the September data, where the sedges stand falls between the vegetated and the non-vegetated sites and is quite distinct from the mature heather. The 1984 data are however in broad agreement with the ground radiometer data collected that month (section 4.5) although the separation of the heather and the sedges is recorded more clearly in the radiometer data.

The main differences between the September 1983 and the August 1984 data sets in this band lie in the separations within and between the two broad

Site	Minimum DN	Maximum DN	Mean	Standard deviation	Coefficient of variation
1	50	56	54.10	0.889	1.643
4	66	71	69.02	1.079	1.563
5	54	62	57.91	1.581	2.730
7	54	61	57.89	1.479	2.555
8	54	63	59.01	1.749	2.964
9	49	57	52.27	1.261	2.412
10	51	59	53.05	1.224	2.308
12	50	53	51.46	0.733	1.420
14	49	59	51.25	1.094	2.134
17	49	51	49.71	0.579	1.164
18	49	54	50.94	1.003	1.969
21	47	57	50.06	1.174	2.345
22	49	53	51.12	0.793	1.551
23	50	52	51.19	0.560	1.094
24	56	61	58.69	1.154	1.966

Table 6.3a Descriptive statistics of response at test sites, **ATM 2**

Site	4	5	6	7	9	10	12	14	17	18	21	22	23	25
1	7.58	1.55	1.60	1.86	0.85	0.49	1.62	1.43	3.01	1.67	1.96	1.77	2.00	3.23
4	-	4.18	4.35	3.54	7.16	6.93	9.69	8.18	1.17	8.68	9.19	9.56	1.09	3.95
5		-	0.01	0.33	1.99	1.73	2.79	2.49	3.81	2.70	2.85	2.86	3.14	0.96
6			-	0.35	2.05	0.79	2.91	2.58	3.99	2.80	2.95	2.98	3.29	1.00
7				-	2.24	2.00	3.04	2.73	4.01	2.93	3.06	3.10	3.39	0.51
9					-	0.32	0.40	0.43	1.40	0.58	0.91	0.56	0.59	3.50
10						-	0.81	0.78	1.86	0.95	1.25	0.96	1.04	3.21
12							-	0.53	1.35	0.41	0.73	0.54	0.21	4.61
14								-	0.93	0.15	0.47	0.07	0.04	4.23
17									-	0.79	0.20	1.04	1.30	6.50
18										-	0.40	0.10	0.16	4.56
21											-	0.54	0.65	3.71
22												-	0.05	4.98
23													-	5.64

Table 6.3b Dnorm values: spectral separation of test sites, **ATM 2**

groups of vegetated and partly or wholly exposed sites. In the 1984 data all elements of one group are separated from all elements of the other. There is little discrimination between the vegetated sites but good separation between the partially and the fully exposed surfaces (table 6.3). In the 1983 data the overall separation of wholly or partially exposed sites from the complete canopies is lower and the exposed surfaces are not clearly separated from the regenerating sites. There is however clearer separation between specific pairs of vegetated sites.

The discussion in section 6.2 suggested that the bracken and sedges classes are most likely to show variation in response over time and this seems to be the case in ATM 2. The position of the Eriophorum stand relative to the other canopies is considerably different in the two data sets. The response of the bracken stand is more stable, but in the 1984 data is markedly separate from the darker canopies of the over-age heather with which it is confused in the 1983 data. The bracken and sedges are more clearly separated from each other in the 1984 data, but, as in the 1983 data, further spectral information is needed to isolate both these stands from all other sites.

6.4.2 ATM 3

The distribution of the test sites in ATM 3 is similar to that in ATM 2. There is a single clear division between the vegetated and the partially or wholly exposed areas although this division is stronger in ATM 2. Although the mean responses of the vegetated sites are more widely spaced in ATM 3, the statistical separations are similar for the two bands (table 6.4). The response of the Eriophorum stand is slightly higher relative to the other sites and it is therefore largely separate from the established heather classes with which it was confused in the 1983 data. However, this places it closer to the bracken stand and overlapping with the regenerating surfaces.

The slightly higher response of the bracken stand means that it is clearly

Site	Minimum DN	Maximum DN	Mean	Standard deviation	Coefficient of variation
1	47	56	54.03	1.142	2.114
4	62	68	65.15	1.240	1.903
5	52	59	55.52	1.357	2.444
7	53	58	55.64	1.209	2.174
8	51	61	56.49	1.924	3.406
9	47	57	50.19	1.341	2.671
10	48	56	50.29	1.037	2.063
12	50	53	51.46	0.733	3.415
14	46	54	48.04	0.978	2.037
17	46	50	47.76	0.719	1.506
18	46	52	48.32	1.259	2.606
21	45	53	47.23	1.045	2.212
22	47	51	48.99	0.846	1.726
23	51	54	52.54	0.545	1.036
24	51	56	53.65	0.858	1.600

Table 6.4a Descriptive statistics of response at test sites **ATM 3**

Site	4	5	6	7	9	10	12	14	17	18	21	22	23	25
1	4.67	0.60	0.68	0.80	1.55	1.72	3.07	2.83	3.37	2.38	0.15	2.54	0.88	0.51
4	-	3.71	3.88	2.74	5.80	6.53	8.83	7.72	8.88	6.73	4.11	7.75	7.07	4.43
5		-	0.05	0.29	1.98	2.19	3.49	3.21	3.74	2.75	0.41	2.96	1.57	0.16
6			-	0.27	2.14	2.38	3.83	3.48	4.09	2.96	0.48	3.24	1.77	0.23
7				-	1.93	2.09	3.09	2.91	3.30	2.56	0.63	2.71	1.60	0.46
9					-	0.04	0.82	0.93	1.18	0.72	1.56	0.55	1.25	2.09
10						-	1.03	1.12	1.44	0.85	1.71	0.69	1.42	2.36
12							-	0.32	0.59	0.12	2.91	0.29	3.36	3.96
14								-	0.16	0.13	2.71	0.53	2.96	3.55
17									-	0.29	3.18	0.79	3.78	4.24
18										-	2.31	0.32	2.34	2.99
21											-	2.44	0.98	0.30
22												-	2.55	3.29
23													-	1.66

Table 6.4b Dnorm values: spectral separation of test sites, **ATM 3**

separated from the heather groups, but, as noted above, is more readily confused with the Eriophorum stand and the partially vegetated areas of pioneer heather growth. The statistical separation of the over-age and the young heather canopies is broadly similar to that in ATM 2 which means that the critical distinctions between these two groupings is not made. The distribution and separation within the partly exposed areas is similar to that of ATM 2 and the important distinction between newly burnt sites and other exposed surfaces is maintained.

The parallels between ATM 2 and ATM 3 found here are in line with those found in the September 1983 data. The clearest difference between the two bands is in the positioning of the Eriophorum stand and this occurs in both data sets. Tables 6.3 and 6.4 show that there is little to choose between ATM 2 and ATM 3 for optimising the statistical separation of the sample areas. On average ATM 2 has greater discriminating information but ATM 3 allows clearer definition of a number of sites. In particular the sedges site is best separated from the rest of the vegetated canopies in ATM 3.

6.4.3 ATM 5

In ATM 5 the recently burnt sites have a low response and are grouped with the over-age and the mature heather stands. The bracken is placed more firmly with the sites of young heather growth (sites 9,10 and 12) and the response of the Eriophorum stand is close to that of the pioneer heather stands. This has the effect of giving the Eriophorum canopy some confusion with virtually all other canopies (table 6.5). With these exceptions the relative positions of the sample sites are similar to those of ATM 2 and ATM 3.

The sites are divided into those with full canopies at the lower limit of response and the regenerating or exposed surfaces which have a higher response although the two groups are not as tightly defined as they are in ATM 2. Compared to both ATM 2 and ATM 3 the means of both vegetated and non-vegetated sites are more clearly separated but the internal variation

Site	Minimum DN	Maximum DN	Mean	Standard deviation	Coefficient of variation
1	54	70	65.95	2.120	3.215
4	68	76	70.87	1.946	2.745
5	59	67	63.82	1.794	2.811
7	61	69	64.37	1.894	2.943
8	64	70	66.91	1.282	1.915
9	57	67	62.37	1.532	2.457
10	60	68	63.98	1.708	2.669
12	60	66	63.18	1.884	1.881
14	56	66	60.64	2.002	3.302
17	56	61	58.29	0.941	1.615
18	55	66	60.44	2.353	3.890
21	52	64	58.27	2.408	4.132
22	56	67	60.71	1.601	2.637
23	60	65	62.68	0.797	1.271
24	55	61	57.39	1.153	2.009

Table 6.5a Descriptive statistics of response at test sites, ATM 5

Site	4	5	6	7	9	10	12	14	17	18	21	22	23	25
1	1.21	0.54	0.39	0.28	0.98	0.51	0.84	1.29	2.50	1.23	2.03	1.41	1.12	2.44
4	-	1.89	1.69	1.23	2.45	1.89	2.45	2.59	4.36	2.43	3.56	2.87	2.99	4.25
5		-	0.15	1.00	0.44	0.05	0.21	0.84	2.02	0.82	1.58	0.92	0.44	1.96
6			-	0.80	0.58	0.11	0.38	0.96	2.14	0.93	1.70	1.05	0.63	2.08
7				-	1.61	0.98	1.51	1.91	3.87	1.78	2.98	2.15	2.03	3.75
9					-	0.50	0.30	0.49	1.65	0.50	1.24	0.53	0.14	1.59
10						-	0.28	0.90	2.61	0.87	1.68	0.99	0.52	2.08
12							-	0.80	2.29	0.78	1.70	0.89	0.25	2.21
14								-	0.80	0.05	0.58	0.02	0.73	0.77
17									-	0.65	0.12	0.95	2.49	0.01
18										-	0.48	0.07	0.71	0.63
21											-	0.68	1.78	0.11
22												-	0.82	0.91
23													-	2.41

Table 6.5b Dnorm values: spectral separation of test sites, ATM 5

of each class is also slightly higher (table 6.5) so that the statistical separation of the sites is generally lower than that of the blue or green bands. This was also found for the September 1983 data. The slight increase in spatial resolution has reduced the variance levels of most classes, and particularly the regenerating areas, across all visible bands.

In summary the three visible bands show broadly similar patterns of response for the sample sites examined here. There are however notable differences between bands in the relative response of the newly burnt heather sites and the sedges and, to a lesser degree, the bracken stands. ATM 3 carries unique discriminatory information on the distribution of sedges and heather. These differences between bands were less marked in the 1983 data. The statement of chapter 5, that "the information in one waveband is generally duplicated somewhere in the other two" is therefore less accurate when applied to the 1984 data set.

The general ordering of sites in the 1984 data is however similar to that of 1983. The only major difference, consistent across all bands, is that the over-age heather stands have a more uniform and lower response in the 1984 data and the distinction of the mature stand is lost.

6.4.4 ATM 7

The range of response is high in ATM 7 and the means of most classes are well separated. The exposed peat surface and the bracken stand are particularly well isolated at the lower and upper limits of reflectance respectively. The internal variance of each class is high however and apart from these two sites the average separation of the sample sites is similar to that of the 1983 data. The ordering of the sites is approximately the reverse of that in the visible bands and the near-IR response increases in approximate proportion to vegetation amount. However most of the heather stands retain their positions relative to each other. This was also the case in the 1983 data and the distribution of sites in this band at the two dates is very similar.

In both cases the lowest response is found over the exposed and partly vegetated surfaces. In the 1984 data the pioneer heather sites included in this group have a very high internal variation (table 6.6) and they are not statistically separate from the adjoining cluster of mature and over-age heather stands.

The over-age heathers have a lower response than the mature heather and the mixed Eriophorum/heather stands and the response of the three over-age stands is remarkably similar in this waveband. This means that the over-age stands are more clearly separated as a group from the more variable and higher response of the young heather canopies (table 6.6). The two classes are confused in the visible wavebands and in the 1983 data this confusion extends to the near-IR, although specific pairs of elements from each group reach levels of separation similar to the 1984 data. Their increased separation in the 1984 data is important for management but relies heavily on the uniformity of response in the over-age stands, which may not exist throughout the moors.

The Eriophorum canopy has a high radiance in the near-IR and is separated from all other classes except the surrounding stands of young and mature heather. The confusion with these classes is greater than that in the 1983 data. The Eriophorum stand is however separated from these stands in ATM 3 and the use of these two bands will isolate the Eriophorum canopy (figure 6.1).

In summary the pattern of response in the near-IR, relative to that in the visible bands, is similar at both dates. The greater uniformity of response from the over-age heathers means however that the over-age and young heathers are more clearly and uniformly discriminated in the 1984 data.

The distribution of the test sites in this waveband is close to that in the August 1983 and 1984 ground radiometer data, and, as in the radiometer data, the greatest changes over time lie in the visible bands. The 1984 ground radiometer data however suggest that the newly burnt site has a

Site	Minimum DN	Maximum DN	Mean	Standard deviation	Coefficient of variation
1	102	173	157.00	9.099	5.790
4	53	66	59.48	2.861	4.810
5	54	95	75.61	8.693	11.496
7	57	109	75.46	9.107	12.069
8	65	105	81.26	7.864	9.678
9	69	102	90.48	6.122	6.766
10	77	101	89.04	5.197	5.836
12	83	108	98.52	4.134	4.196
14	53	96	86.84	4.643	5.346
17	75	85	79.08	1.965	2.484
18	69	91	79.03	4.563	5.770
21	49	94	79.76	6.308	7.909
22	71	93	82.28	4.196	5.100
23	85	99	92.44	2.176	2.354
24	45	81	49.41	7.197	14.564

Table 6.6a Descriptive statistics of response at test sites, **ATM 7**

Site	4	5	6	7	9	10	12	14	17	18	21	22	23	25
1	8.15	4.57	4.48	4.46	4.37	4.75	4.42	5.11	7.04	5.70	1.02	5.62	5.73	1.11
4	-	1.40	1.34	2.03	3.45	3.67	5.58	3.65	4.06	2.64	2.61	3.23	6.54	3.46
5		-	0.01	0.34	1.00	0.97	1.79	0.84	0.33	0.26	2.70	0.52	1.55	3.04
6			-	0.34	0.99	0.95	1.74	0.83	0.33	0.27	2.58	0.51	1.51	2.90
7				-	0.66	0.61	1.44	0.45	0.22	0.18	3.54	0.08	1.11	3.97
9					-	0.13	0.78	1.34	1.41	1.07	5.54	0.80	0.24	6.28
10						-	1.02	0.22	1.39	1.02	6.09	0.72	0.46	7.01
12							-	1.33	3.19	2.23	8.90	1.95	0.96	1.04
14								-	1.17	0.84	6.28	0.52	0.82	7.31
17									-	0.00	8.86	0.52	3.23	1.15
18										-	5.09	0.36	1.98	5.99
21											-	5.97	1.20	0.58
22												-	1.60	7.06
23													-	1.51

Table 6.6b Dnorm values: spectral separation of test sites, **ATM 7**

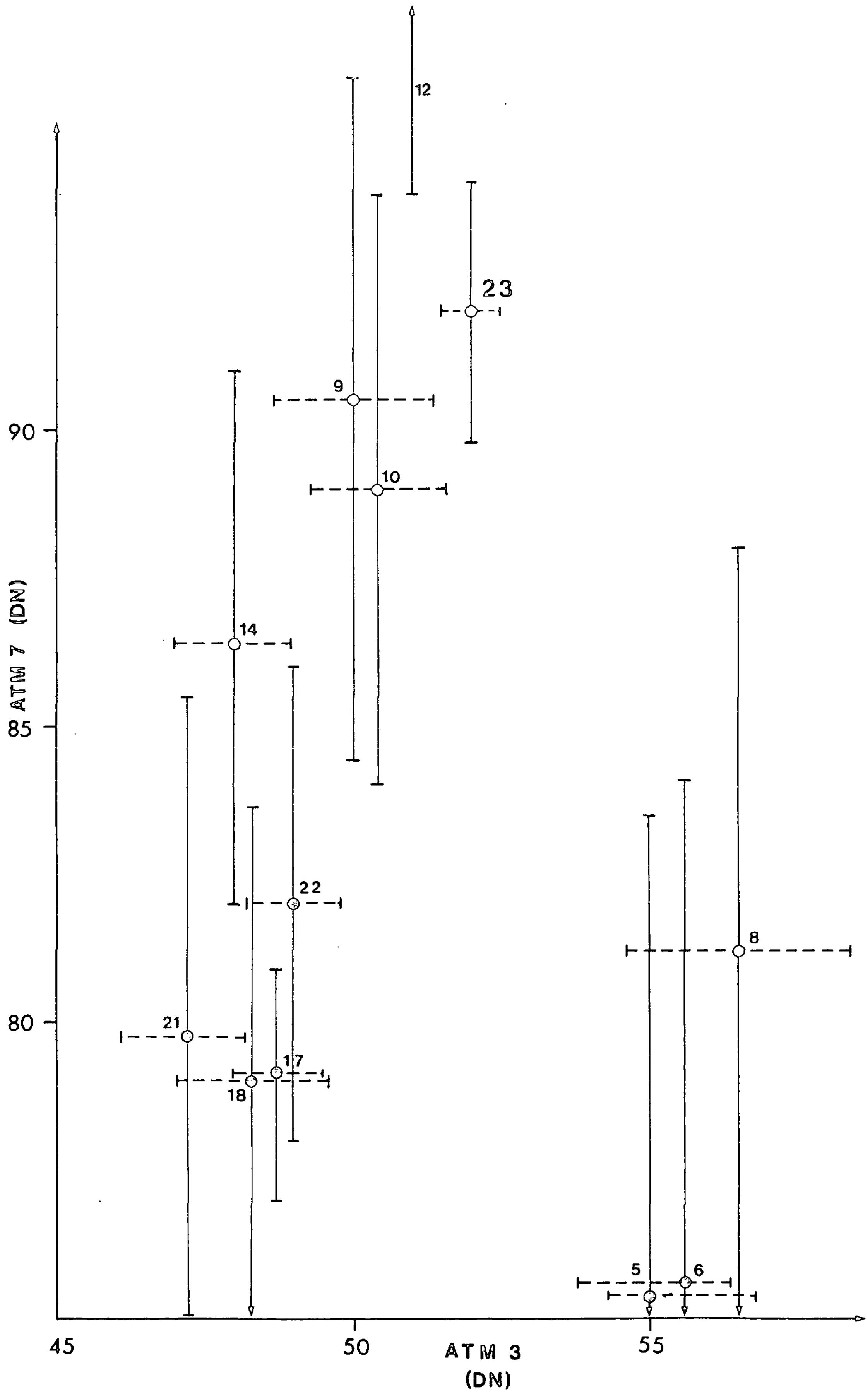


Figure 6.1 Spectral response of selected test sites in the visible (TM 2) and near-IR (TM 4) bands, August 1984 ATM data. Numbers correspond to test sites identified in table 6.1.

uniform low response which is easily identifiable from all other sites, whilst the airborne sensor data places it with the mature and over-age heather sites. This radiometer result is however confirmed in later work with imagery acquired closer to the date of the radiometer measurements and the end of the burning season. The variability in response at the regenerating sites, which overlap all other classes, is also predicted from the radiometer data. The overlap between the response of the heather and the Eriophorum stand is present in the airborne data but to a lesser degree than suggested by the radiometer data. The 1984 ground radiometer data are a better predictor of the separations possible in the airborne data than are the 1983 data for the same canopies.

6.4.5 ATM 9 and ATM 10

This discussion of the response in the mid-IR bands concentrates on ATM 10 for the sake of consistency with chapter 5. In fact the noise present in ATM 9 in the 1983 data is not present in the 1984 data. In general however the two wavebands carry very similar information (table 6.7, figure 6.2), although the higher ATM 9 response of the bracken stand means that it is isolated from all other stands in this combination. As found in the 1983 data the mid-IR bands show the same general pattern of response as the visible wavebands. The bracken and sedges stands have very similar responses in the mid-IR and this situation is closest to that in ATM 3. In the 1983 data the positioning of these two stands was closest to that in ATM 5. Otherwise the ordering of the classes is similar for the two dates.

The mature and the over-age heather canopies have the lowest mid-IR radiance. One of the young heather stands is placed with this group, the other two sites of young heather have a slightly higher radiance and are close in spectral terms to the Eriophorum and the bracken classes.

The means of all the vegetated sites fall within 5 DN (table 6.7). There is therefore little statistical separation between them, although specific pairs of sites can be isolated and this was also the situation in the 1983

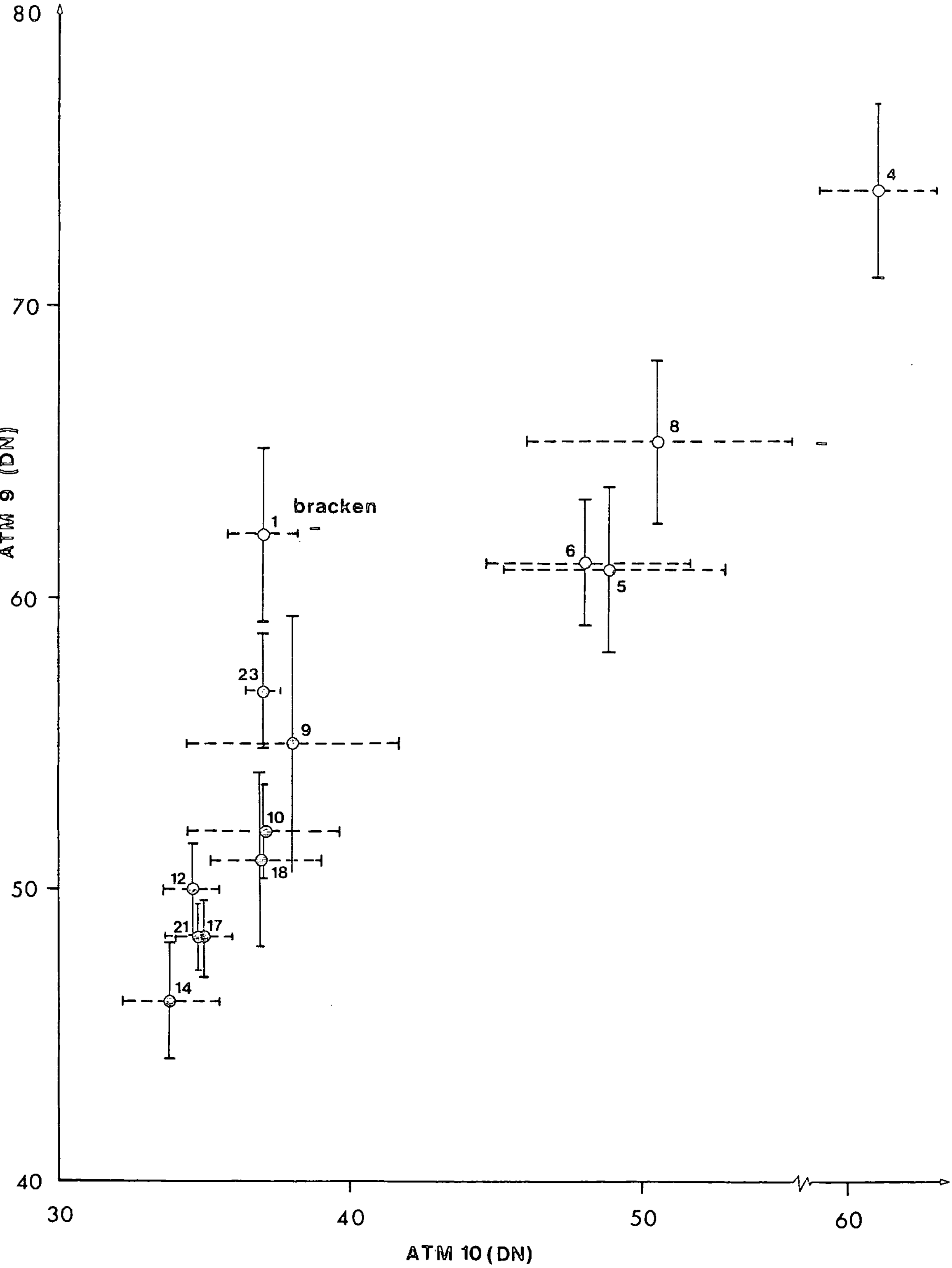


Figure 6.2 Spectral response of selected test sites in the mid-IR wavebands, August 1984 ATM data.

Site	Minimum DN	Maximum DN	Mean	Standard deviation	Coefficient of variation
1	42	68	62.39	3.357	5.380
4	63	83	74.05	3.143	4.244
5	54	68	61.21	2.670	4.361
7	39	58	48.67	3.693	7.587
8	54	72	65.85	3.737	5.675
9	46	72	54.95	4.307	7.838
10	48	66	52.78	2.700	5.115
12	45	55	50.15	1.639	3.268
14	43	56	48.13	1.889	3.925
17	44	53	48.48	1.742	3.593
18	44	63	51.68	3.203	6.198
21	42	65	48.44	2.630	5.430
22	46	64	50.30	2.399	4.769
23	51	59	55.55	1.621	2.917
24	51	60	55.09	1.911	3.468

Table 6.7a Descriptive statistics of response at test sites, **ATM 9**

Site	Minimum DN	Maximum DN	Mean	Standard deviation	Coefficient of variation
1	29	39	37.16	1.208	3.250
4	53	66	61.89	2.650	4.281
5	37	60	48.81	4.211	8.628
7	39	58	48.67	3.693	7.587
8	36	61	50.41	4.948	9.816
9	34	55	38.98	3.638	9.333
10	34	51	37.32	2.664	7.139
12	33	40	34.58	0.833	2.408
14	32	47	33.86	1.407	4.156
17	33	37	34.59	0.693	2.003
18	34	43	37.06	1.985	5.357
21	33	50	34.82	1.991	5.716
22	33	47	35.26	1.349	3.827
23	37	40	37.95	0.541	1.426
24	39	52	48.60	2.336	4.807

Table 6.7b Descriptive statistics of response at test sites, **ATM 10**

Site	4	5	6	7	9	10	12	14	17	18	21	22	23	25
1	1.80	0.19	0.20	0.21	0.97	1.59	2.45	2.72	0.99	1.63	0.97	2.10	1.37	1.22
4	-	2.21	2.41	1.48	2.56	3.64	5.00	5.15	1.84	3.53	3.14	4.29	3.88	3.69
5		-	0.02	0.41	0.90	1.57	2.57	2.87	0.95	1.62	0.87	2.15	1.32	1.14
6			-	0.44	0.98	1.75	2.94	3.26	0.99	1.79	0.99	2.41	1.52	1.32
7				-	1.11	1.72	2.55	2.79	1.06	1.75	1.15	2.21	1.55	1.41
9					-	0.31	0.81	1.10	0.43	0.44	0.28	0.69	0.10	0.21
10						-	0.61	1.01	0.32	0.19	0.80	0.49	0.64	0.79
12							-	0.57	0.14	0.31	1.68	0.04	1.66	1.83
14								-	0.03	0.70	2.05	0.51	2.12	2.27
17									-	0.23	0.64	0.14	2.10	0.62
18										-	0.93	0.25	0.80	0.93
21											-	1.38	0.32	0.15
22												-	1.31	1.45
23													-	0.21

Table 6.8a Dnorm values: spectral separation of test sites, **ATM 9**

Site	4	5	6	7	9	10	12	14	17	18	21	22	23	25
1	6.70	2.61	3.95	3.17	1.40	1.57	1.52	1.48	3.12	3.05	2.32	1.89	2.53	6.13
4	-	0.67	0.63	1.16	2.44	2.88	4.32	4.59	4.96	3.44	0.02	5.19	5.39	0.18
5		-	0.16	0.19	1.06	1.20	1.71	1.80	1.65	1.17	0.66	1.90	1.85	0.55
6			-	0.44	1.51	1.75	2.56	2.70	2.65	1.86	0.62	2.94	2.94	0.47
7				-	1.06	1.24	1.92	2.04	1.88	1.22	1.13	2.20	2.16	0.99
9					-	0.05	0.44	0.51	0.12	0.27	2.37	0.52	0.38	2.24
10						-	0.43	0.52	0.05	0.40	2.78	0.52	0.36	2.64
12							-	0.10	0.69	1.14	4.12	0.04	0.24	3.94
14								-	0.86	1.29	4.37	0.08	0.38	4.19
17									-	0.80	4.67	0.95	2.72	4.45
18										-	3.29	1.29	1.28	3.09
21											-	0.04	5.07	3.94
22												-	0.37	4.71
23													-	4.86

Table 6.8b Dnorm values: spectral separation of test sites, **ATM 10**

data. The low statistical separation is partly due to the high internal variance in the young heather stands, which is unexpected and approaches that of the pioneer regenerating areas. In the 1983 data the sites of young heather had a variance similar to that of other vegetated stands. The young stands were therefore more easily recognisable from all other vegetated stands. ATM 3 is therefore still the only waveband which gives an acceptable separation between the Eriophorum and the heathers.

The Eriophorum is however separated from most of the other canopies in the mid-IR and for some of these, notably the pioneer heathers, this is higher than the same statistics for ATM 3 (table 6.8). There is a very clear division between the fully established canopies and the group of fully and partially exposed surfaces. The strength of the separation is however rather weaker than that of ATM 2 and ATM 3 because of the high internal variance of the pioneer areas. This also means that despite the fact that the mean response of the exposed peat surface is well separated from that of the regenerating surfaces, its statistical separation is lower than that for the visible or the near-IR bands.

In summary the 1983 and 1984 data are in broad agreement for the mid-IR wavebands and the ordering and separation of the test sites are similar in both data sets. The bracken stand is positioned differently but this has little effect on its overall separation from the remaining stands.

6.4.6 ATM 11

In contrast to the 1983 data, the absolute range of response and the internal variance of each class in ATM 11 are not much above those of all other wavebands. The combined effect however is to produce a Dnorm matrix very similar to that of the 1983 data (table 6.9). The bracken stand has the lowest response. There is some confusion between the bracken stand and elements of the neighbouring cluster of vegetated canopies which have high internal variance. This level of confusion was not present in the 1983 data as the bracken was more clearly isolated at the lower limit of

Site	Minimum DN	Maximum DN	Mean	Standard deviation	Coefficient of variation
1	46	53	49.21	1.270	2.581
4	70	80	74.03	2.434	3.287
5	54	83	68.35	6.067	8.876
7	56	79	70.00	3.990	5.701
8	57	76	66.39	4.151	6.253
9	48	72	57.24	4.454	7.782
10	48	71	56.80	3.555	6.258
12	49	61	54.36	2.124	3.908
14	50	70	53.97	1.938	3.591
17	53	58	55.56	1.088	1.958
18	54	68	58.98	1.938	3.286
21	55	96	60.14	3.446	5.730
22	49	60	54.22	1.381	2.547
23	53	58	55.13	1.072	1.945
24	68	75	69.64	2.446	3.513

Table 6.9a Descriptive statistics of response at test sites, **ATM 11**

Site	4	5	6	7	9	10	12	14	17	18	21	22	23	25
1	6.41	2.15	2.35	2.15	0.38	0.04	1.27	1.26	1.35	0.03	4.78	0.75	0.45	5.38
4	-	1.41	2.08	1.51	3.64	4.62	7.84	6.91	8.17	5.36	2.70	6.66	7.50	2.76
5		-	0.02	0.17	1.25	1.67	2.82	2.66	2.90	1.90	0.29	2.44	2.29	0.37
6			-	0.20	1.32	1.79	3.11	2.90	3.21	2.05	0.34	2.66	2.53	0.44
7				-	1.33	1.72	2.74	2.60	2.80	1.93	0.01	2.41	2.27	0.08
9					-	0.26	0.99	1.02	1.01	0.34	2.20	0.75	0.25	2.39
10						-	0.78	0.85	0.81	0.06	3.10	0.51	0.20	3.39
12							-	0.32	0.01	0.88	6.60	0.31	2.46	7.50
14								-	0.35	0.94	5.57	0.51	2.10	6.20
17									-	0.92	7.00	0.33	0.20	8.01
18										-	3.77	0.54	0.35	0.16
20											-	5.20	5.91	0.14
22												-	1.42	5.81
23													-	6.87

Table 6.9b Dnorm values: spectral separation of test sites, **ATM 11**

response. There is generally very little discrimination between any of the vegetated canopies.

As in the 1983 data the response of the young heather classes is split, one is similar to the mature heather canopy, the other two have a slightly higher response but this is not sufficient to isolate them from the fully developed heather canopies. Thus elements of the over-age and the young heather classes inter-mingle and there is little suggestion of any group identity within the vegetated areas.

The division between the vegetated and the non-vegetated sites is clear in this waveband. The new burn sites fall as expected with the exposed sites and have a similar emittance to the least vegetated of the pioneer sites and the exposed peat surface. The new burn sites are grouped with vegetated areas in ATM 5. It is important for management however that they are correctly identified as non-vegetated sites and the use of ATM 11 and ATM 7 will isolate them completely (figure 6.3)

6.4.7 Summary

The pattern of response in the August 1984 data is broadly similar to that in the September 1983 data. The differences between the two data sets are mainly in the visible wavebands. At the top level of classification, between heather, bracken, sedges and exposed surfaces, the greatest difference between the two data sets is in the relative response of the bracken and the sedges and their subsequent confusion and discrimination from all other sites. In the 1984 data the response of the Eriophorum canopy is similar to that of the young and the mature heather canopies in both ATM 2 and ATM 5, and similar to the young heathers and the bracken stands in ATM 3. The bracken stand is placed at the upper limit of response of the vegetated canopies or with the partially vegetated surfaces in all the visible bands. In the 1983 data the response of the bracken stands is more closely aligned with that from the vegetated surfaces and the Eriophorum stand is consistently grouped with the young heathers and

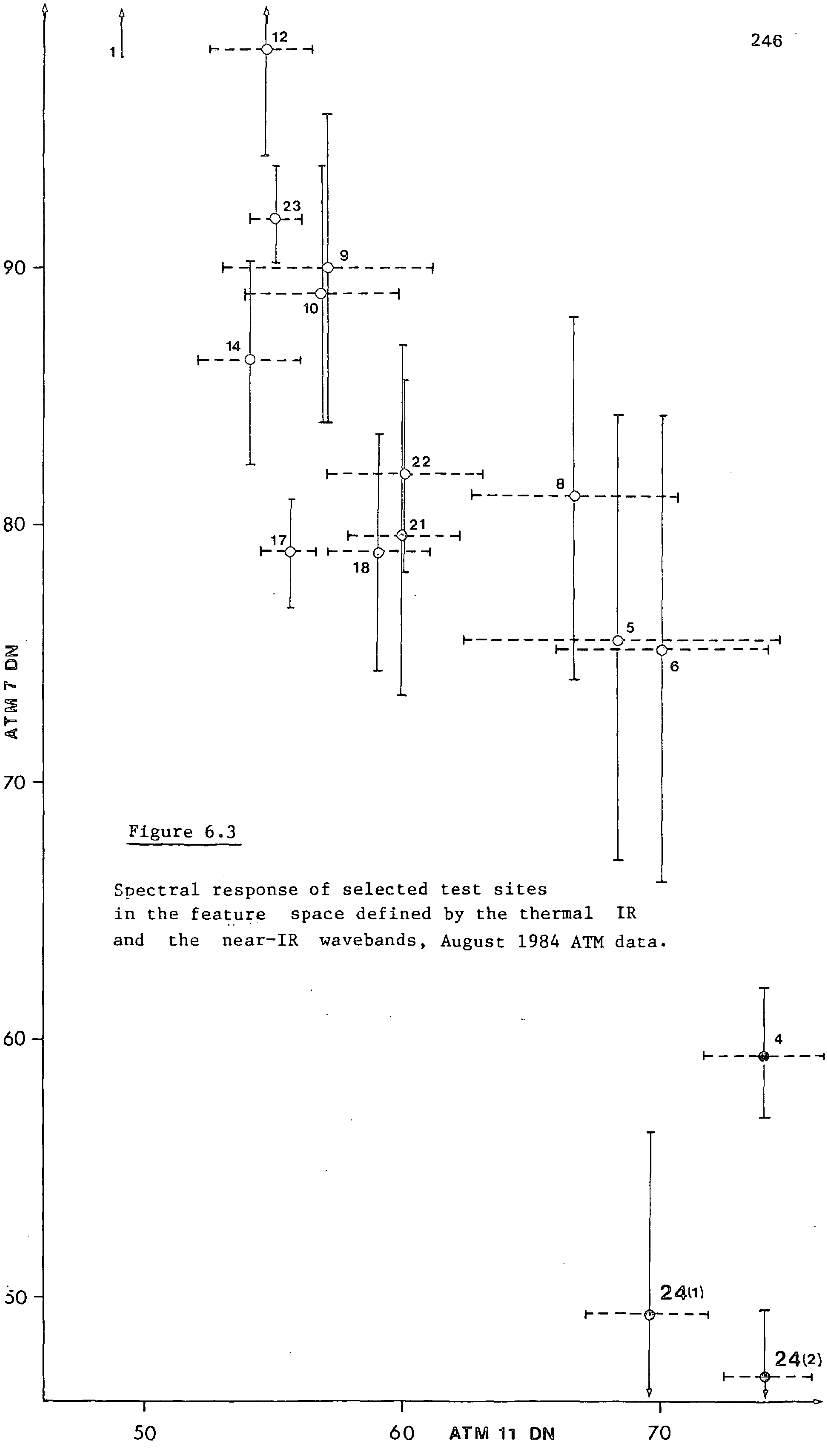


Figure 6.3

Spectral response of selected test sites in the feature space defined by the thermal IR and the near-IR wavebands, August 1984 ATM data.

the regenerating surfaces. In the near-IR however the position of these two canopies relative to all other stands is similar for both dates.

In the 1983 data the lowest response in the visible bands is from the mature heather canopy, in the 1984 data this is replaced by the over-age stands and this is consistent across all the visible bands. Otherwise there are no dramatic changes in the ordering and division of the heather sites, although, as noted in section 6.5.4, there is some improvement in the separation of the over-age and the young heather canopies.

Figure 6.4 is the 1984 counterpart of figures 5.18 in the previous chapter, and outlines the differences in the amount and type of discriminatory information between the two data sets.

6.5 August 1984 data: structure and dimensionality

As in chapter 5 the correlation matrices and principal components were calculated for each test site to identify the main sources of independent variation in the data set. The TD measure was calculated for all pairs of classes and all combinations of wavebands to determine whether the discriminatory information in the full data set was significantly affected by the changes in the discriminatory power of individual wavebands and the degree of inter-band correlation.

6.5.1 Correlation matrices

The correlation matrices from the 1984 data are shown in table 6.10. In sites 5 and 6, areas of pioneér regrowth, the positive correlation of ATM 5 and ATM 7 affects the relationship of ATM 5 to all other wavebands. This change was not expected from the results of the previous section or knowledge of the factors controlling radiance in these wavebands. The structure of the remaining spectral information for these sites is similar to that in the 1983 data. In contrast, at site 9 the three visible bands retain their strong correlation in the 1984 data (r >0.82) although the mid-IR bands are less closely related to the visible wavelengths. At site

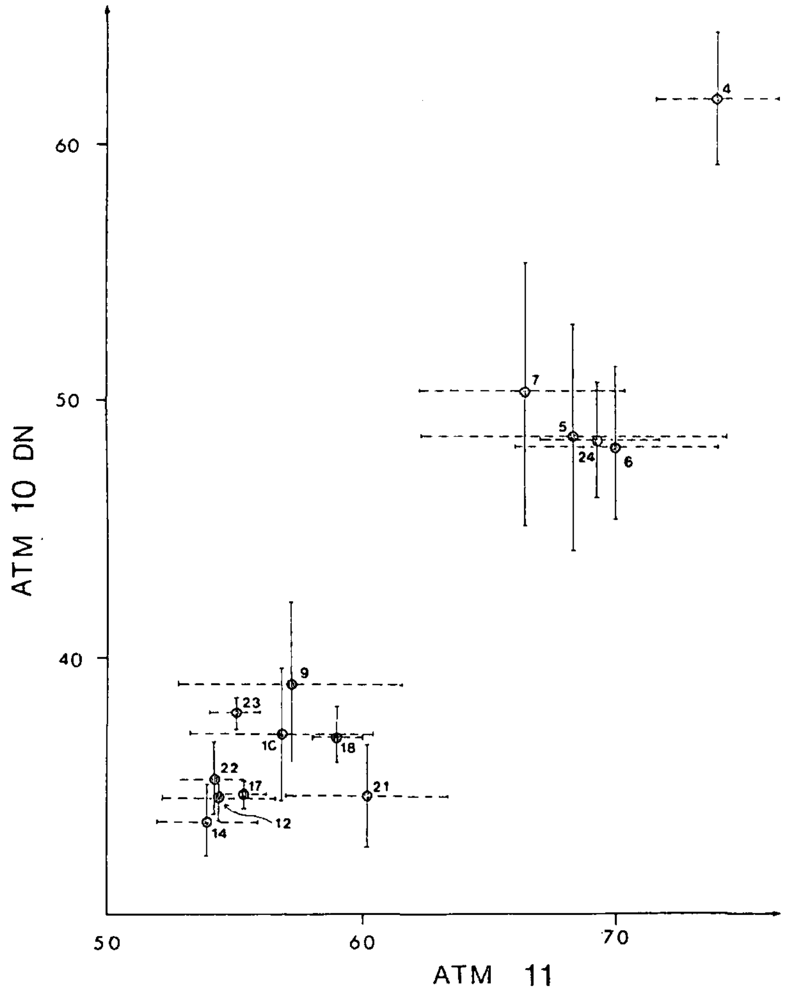
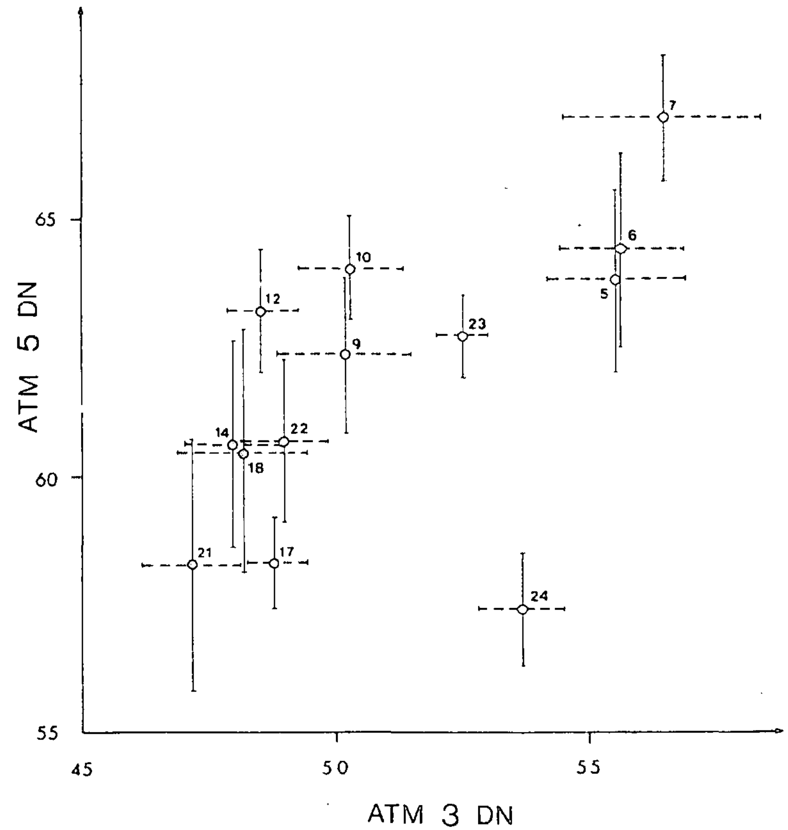


Figure 6.4

Spectral response of selected test sites in the feature space defined by
a. two visible bands
b. mid-IR and thermal IR bands.

Parallel to figure 5.13 (chapter 5)



Site 1 bracken

3	.81					
5	.84	.91				
7	.84	.86	.93			
9	.69	.73	.75	.84		
10	.79	.82	.82	.89	.84	
11	.40	.37	.45	.55	.46	.48
ATM	3	5	7	9	10	11

Site 23 Eriophorum

3	.39					
5	.36	.63				
7	.13	.46	.65			
9	.06	.19	.19	.16		
10	.19	.37	.28	.11	.27	
11	-.09	-.20	-.41	-.61	-.02	.05
ATM	3	5	7	9	10	11

Site 4 exposed peat surface

3	.84					
5	.36	.64				
7	.05	.33	.60			
9	.46	.54	.57	-.02		
10	.38	.48	.59	-.20	.83	
11	-.13	.01	.10	-.10	.11	.30
ATM	3	5	7	9	10	11

Site 5 partly vegetated peat surface

3	.88					
5	-.33	-.17				
7	-.77	-.63	.77			
9	.66	.70	-.23	-.60		
10	.86	.82	-.51	-.90	.80	
11	.72	.57	-.79	-.94	.56	.86
ATM	3	5	7	9	10	11

Site 6 partly vegetated peat surface

3	.73					
5	-.41	-.01				
7	-.72	-.25	.80			
9	.57	.55	-.01	-.29		
10	.84	.52	-.55	-.89	.54	
11	.74	.34	-.68	-.92	.42	.89
ATM	3	5	7	9	10	11

Site 9 young heather, incomplete cover

3	.82					
5	.48	.51				
7	-.25	-.11	.54			
9	.46	.53	.04	-.36		
10	.57	.54	-.07	-.62	.88	
11	.21	-.02	-.41	-.76	.37	.61
ATM	3	5	7	9	10	11

Site 10 young heather, complete cover

3	.85					
5	.31	.24				
7	-.19	-.22	.76			
9	.48	.60	-.05	-.28		
10	.65	.76	-.24	-.62	.76	
11	.33	.35	-.57	-.85	.44	.73
ATM	3	5	7	9	10	11

Site 12 young heather, complete cover

3	.61					
5	.66	.70				
7	.50	.43	.68			
9	.19	.30	.22	.02		
10	.22	.34	.21	-.28	.46	
11	-.16	-.11	-.18	-.60	.14	.47
ATM	3	5	7	9	10	11

Site 14 mature heather

3	.85					
5	.66	.68				
7	.14	.15	.73			
9	.49	.50	.38	.02		
10	.71	.76	.33	-.30	.57	
11	.28	.29	-.25	-.65	.29	.63
ATM	3	5	7	9	10	11

Site 17 over-age heather

3	.48					
5	.61	.58				
7	.38	.23	.70			
9	.34	.35	.29	.35		
10	.43	.68	.45	.18	.35	
11	.09	.19	-.04	-.26	-.09	.19
ATM	3	5	7	9	10	11

Table 6.10 Inter-band correlations at selected test sites

10 ATM 5 and ATM 7 are more closely linked in the 1984 data (1983: r=0.53, 1984: r=0.76). There is a general weakening of relationships across all bands over site 12 (r >0.7 only between ATM 5 and ATM 7), but no reversals.

The strong positive correlations between the visible bands and ATM 10 found for the mature canopy in the 1983 data are maintained in the 1984 data for ATM 2 and ATM 3, but the increased correlation between ATM 5 and ATM 7 means that ATM 5 is not linked to the mid-IR bands. There is also some reduction in the strength of the relationships between ATM 3 and ATM 5 for the over-age stands. In general however the inter-band relationships for all the heather canopies, from partial pioneer growth to over-age stands, are broadly similar to those of the 1983 data although the degree of correlation is generally weaker. There is also a positive link between ATM 5 and ATM 7 for a number of sites which was not present so consistently in the 1983 data.

The exposed peat, the bracken and the sedges classes show greater differences in structure between the two dates. In the two samples taken within the exposed peat area the strong relationship found in the 1983 data between the visible wavebands (r >0.93) is retained between ATM 2 and ATM 3 (minimum r=0.84) and to a lesser extent between ATM 3 and ATM 5 (minimum r=0.64), but is weak for ATM 2 and ATM 5 in one case, where r falls to 0.36. As in the 1983 data the near-IR band has little correlation with any other band at these sites, but the relationship between the visible and the mid-IR is reduced from its 1983 level. One sample shows high correlation between the mid- and the thermal IR, as in 1983, the other shows only a weak relationship.

There is similar variation in structure between different samples of the bracken stand and this was also found for the 1983 data. Most however show strong positive relationships between the visible and the near/mid-IR bands and in one sample these high correlations also extend to the thermal band. This contrasts with the generally low correlations found in the 1983 data. The strong correlations found between the visible and the mid-IR bands in the 1983 Eriophorum data are largely absent in the 1984 data.

6.5.2 Principal components analysis

The results of a principal components analysis on the 7 ATM bands reflect the changes in structure outlined by the correlation matrices. For most classes the variance in the data set is adequately expressed by three independent axes which together account for over 90% of the variance (table 6.11). Where there is low interband correlation 4 or 5 components are needed to account for this amount of variance. The eigenvalues for all the heather classes are similar at the two dates. As expected the peat surface, the sedges and the bracken stand show the greatest differences. The results of chapter 5 showed that intrinsic dimensionality is not in itself a particularly good predictor of the ease with which sites can be separated by their spectral response. In this case however it demonstrates the change over time in the type and amount of spectral information needed to give an adequate description of each site.

The loadings for the 1984 data are given in table 6.12. In the 1983 data the visible bands and the IR bands which were strongly related to the visible bands had high loadings on the first component. For sites 5 and 6 in the 1983 data all bands loaded equally onto the first component. In sites 7 and 10 ATM 5 varied independently to the other wavebands and this variation was the basis for the second component. More commonly the second and subsequent components were dominated by the IR bands, the details depending on the relationships between them.

The general trends in the 1984 data are similar except where ATM 5 and ATM 7 are positively correlated. When ATM 7 appears with a negative loading on the first component in this situation ATM 5 also has a negative loading. This occurs in sites 9 and 10, although the highest loading of ATM 5 for site 10 is on the second component at both dates.

ATM 11 emerges as a strong source of independent information in the second component of the bracken stand, where previously this class had shown the

Site	Component 1	2	3	4	5	6	7
Bracken	77.29	10.73	5.07	2.91	1.96	1.48	0.56
Sedges	40.40	19.63	14.00	10.02	7.72	4.78	3.85
Exposed peat surface	47.81	21.41	16.15	9.82	2.97	1.22	0.52
Partially vegetated surface (site 5)	72.99	17.43	5.51	1.69	1.22	0.80	0.36
Partially vegetated surface (site 6)	64.41	21.49	7.09	3.74	1.72	1.21	0.34
Young heather (site 9)	48.81	32.40	8.75	5.45	2.08	1.67	0.84
Young heather (site 10)	54.50	30.39	7.91	3.02	1.89	1.23	1.06
Mature heather (site 14)	50.78	31.93	8.62	3.65	2.58	1.75	0.69
Over-age heather (site 17)	45.38	20.00	11.63	8.92	7.20	4.55	2.32
New burn	52.42	30.97	8.21	3.47	3.08	1.50	0.35

Table 6.11 Eigenvalues for selected test sites; results of principal components analysis on 7 ATM bands. See text for explanation.

Site 1 bracken

Compt.	1	2	3
ATM 2	.89	.16	.24
3	.92	.21	.15
5	.94	.13	.17
7	.97	.00	-.01
9	.87	-.02	-.44
10	.93	.03	-.19
11	.57	-.81	.12

Site 23 Eriophorum

Compt.	1	2	3	4	5
ATM 2	.48	.10	.64	-.45	-.25
3	.79	.23	.17	.12	.36
5	.87	-.06	.06	.05	.19
7	.78	-.42	-.18	.06	.71
9	.33	.42	-.69	.49	.12
10	.43	.65	-.15	.49	-.37
11	-.56	.65	.11	.03	.41

Site 5 part exposed

Compt.	1	2	3
ATM 2	.25	.29	.28
3	.21	.49	.21
5	.16	.75	.04
7	.25	.27	-.03
9	.20	.38	-.51
10	.26	.10	-.05
11	.24	.34	.02

Site 4 exposed peat

Compt.	1	2	3	4
ATM 2	.73	.12	-.62	-.37
3	.87	.24	-.23	-.31
5	.82	.29	.44	.19
7	.27	.83	.53	.01
9	.82	-.33	-.04	.32
10	.53	-.53	.10	.22
11	.13	-.52	.76	-.52

Site 6 part exposed

Compt.	1	2	3
ATM 2	.90	.26	-.19
3	.46	.67	-.42
5	-.65	.65	.08
7	-.91	.38	-.02
9	.58	.61	.51
10	.96	.00	.05
11	.93	-.22	.11

Site 9 young heather

Compt.	1	2	3	4
ATM 2	.74	.51	.36	-.05
3	.67	.65	.10	-.26
5	.01	.91	.09	.36
7	-.67	.62	-.28	.17
9	.83	.08	-.54	.03
10	.95	-.85	-.22	.05
11	.63	-.61	.21	.39

Site 10 young heather

Compt.	1	2	3
ATM 2	.84	.34	.24
3	.63	.69	.09
5	.16	.93	.10
7	-.64	.68	-.20
9	.63	.06	-.77
10	.92	-.11	.13
11	.74	-.50	.11

Site 12 young heather

Compt.	1	2	3	4	5
ATM 2	.82	.08	.24	-.18	-.48
3	.83	.22	.11	-.14	.35
5	.90	.03	.15	.27	.11
7	.76	-.53	-.09	.22	.01
9	.34	.58	-.71	.12	-.11
10	.22	.87	.06	-.25	.10
11	-.34	.76	.36	.39	-.08

Site 14 mature heather

Compt.	1	2	3
ATM 2	.91	.05	.22
3	.93	.08	.20
5	.69	.69	.05
7	.11	.95	-.05
9	.70	-.08	-.71
10	.86	-.40	.06
11	.40	-.82	.07

Site 17 over-age heather

Compt.	1	2	3	4	5
ATM 2	.76	.05	.20	.26	-.56
3	.79	.36	.07	-.29	.05
5	.85	-.21	.36	.05	.10
7	.63	-.60	.22	.34	.33
9	.58	-.15	-.92	.38	.07
10	.72	.41	-.21	-.35	.06
11	.06	.82	.25	.44	.26

Table 6.12 Component loadings for selected sites. See text for explanation

more conventional visible/near-IR split on the first two components and the thermal band had loaded with the mid-IR bands on the first component. In general however the second and subsequent components are less clearly dominated by one waveband or spectral region than in the 1983 data and there is a continuous variation in loadings, as in interband relationships, from one canopy to another.

This means that each canopy in the 1984 data is best characterised by a slightly different set of wavebands. The suggestion, partly supported in chapter 5, that a combination of wavebands from the visible, near-IR and mid or thermal IR would contain most of the independent information on vegetation status is less widely supported here.

In general therefore the spectral information needed to separate the different canopies is expected to be as specific as it was in the 1983 data but possibly of a different form. This is particularly true of the waveband combinations which isolate the sedges and the bracken canopies from the heather stands. The absolute differences in response between bracken, sedges and exposed surfaces means that more waveband combinations should give a reasonable separation at this upper level of management.

6.7 August 1984 data: multi-spectral separation

The Transformed Divergence (TD) value, described in Chapter 5, was calculated for all combinations of wavebands and all pairs of sites for the August 1984 data. As with the September 1983 data, the separations of bracken, exposed surfaces, heathers and sedges were examined first.

The bracken is clearly separated (TD>1999) from the exposed peat surface by all two-band combinations and is well separated from the partially vegetated surfaces where the minimum TD value is 1979 (ATM 5, ATM 9). The bracken is also clearly separated from the mature heather site (TD=2000) in all but 5 of the possible 2 band combinations. In this case the minimum separation is still high at TD=1829 for ATM 2,ATM 5.

The degree of separation between the bracken and the young heather at sites 9,10 and 12 is much more variable (table 6.18). Waveband combinations which include ATM 7 give the best results across all three of these sites and the waveband combinations which perform least well are also common to all sites. One site of over-age heather (site 17) is well isolated from the bracken (TD>1990) for all waveband combinations. At site 18 ATM 7 is clearly needed for the TD value to reach its maximum, as suggested by section 6.4.4, and there is considerable variation in the discriminating power of other two-band combinations (table 6.13). The combinations which give the lowest separation of these two canopies include those which also discriminate poorly between bracken and the young heather classes, although compared to the 1983 data, the level of separation remains high. The bracken stand is clearly discriminated from the sedges in all but 5 of the two band combinations. The lowest TD value, 1095, is from ATM 5,ATM 7, which gives high TD values for the separation of bracken from the other heather sites.

The bracken stand can therefore be isolated from any other site with a minimum of spectral information, and the choice of wavebands is less important than in the 1983 data. More waveband combinations give an acceptable separation and, particularly important, where spectral content is critical the combinations which give the best and worst separations are the same for all canopies. The surprising exception to this is the case of ATM 5,ATM 7 described above. The cause of the clearer isolations made in the 1984 data is most likely to be the variation in relative response of the bracken stand across the TM wavebands.

The second important constituent of the moorland, the Eriophorum stands, are clearly separated (TD = 2000) from the exposed peat surface in almost all 2 band combinations. The minor exceptions are ATM 5,ATM 7 and ATM 5,ATM 11 where TD=1999, and ATM 5,ATM 9 where TD=1979. Most waveband combinations also give a good discrimination (TD>1999) between the sedges and the partially exposed sites. However a number of sets, mainly those combining visible and mid-IR wavelengths give low TD values for these two

Table 6.13 TD values: spectral separation of bracken and selected test sites, August 1984 ATM data.

Site 1 Site 9

TD	ATM 2	3	5	7	9	10	11
2000			X	X			
				X	X		
				X			X
				X		X	
1999		X		X			
	X			X			
1956			X				X
1918	X						X
1859	X		X				
1854			X		X		
973	X				X		

Site 1 Site 10

TD	ATM 2	3	5	7	9	10	11
2000			X	X			
				X	X		
				X			X
				X		X	
	X	X					
		X		X			
1950			X				X
1932			X		X		
1867	X		X				
1563	X				X		
1072	X						X

Site 1 Site 12

TD	ATM 2	3	5	7	9	10	11
2000			X	X			
				X	X		
				X			X
				X		X	
1999	X	X					
		X	X				
1935			X		X		
1905			X				X
1882	X					X	
1726	X				X		
1204	X					X	

Site 1 Site 14

TD	ATM 2	3	5	7	9	10	11
2000	All combinations						
1999	except....						
1982			X			X	
1950	X						X
1947			X				X
1933	X					X	
1829	X		X				

Site 1 Site 17

TD	ATM 2	3	5	7	9	10	11
2000	All combinations with ATM 7 or ATM 3						
1998	X				X		
1997	X		X				
1994	X						X
1993					X		X
1990			X				X

Site 1 Site 18

TD	ATM 2	3	5	7	9	10	11
2000	All combinations with ATM 7						
1905	X						X
1708			X				X
1674	X		X				
1669	X				X		
1496			X		X		

Table 6.14 TD values: spectral separation of sedges and selected test sites, August 1984 ATM data.

Site 23 Site 7

TD	ATM 2	3	5	7	9	10	11
2000	x			x			
		x		x			
				x		x	
				x			x
						x	x
1916		x					x
1726			x				x
1725			x	x			
1373		x			x		
908			x		x		

Site 23 Site 8

TD	ATM 2	3	5	7	9	10	11
1999							
1963			x			x	
1926			x				x
1765			x	x			
1566			x		x		
1432		x			x		

Site 23 Site 9

TD	ATM 2	3	5	7	9	10	11
2000						x	x
1999				x			x
				x		x	
	x			x			
1982					x		x
658	x				x		
498			x			x	
492			x				x
393			x	x			
57			x		x		

Site 23 Site 10

TD	ATM 2	3	5	7	9	10	11
2000						x	x
1999				x			x
				x		x	
	x			x			
1995	x	x					
1063			x				x
997		x		x			
937				x	x		
643			x		x		
277			x	x			

Site 23 Site 14

TD	ATM 2	3	5	7	9	10	11
2000	x						x
		x					x
			x				x
					x		x
						x	x
1724				x	x		
1696			x		x		
1242	x		x				
817					x	x	
466			x	x			

Site 23 Site 17

TD	ATM 2	3	5	7	9	10	11
2000						x	x
		x					x
				x			x
				x		x	
				x			
1938					x	x	
1927	x		x				
1841			x		x		
1282	x				x		
1247				x	x		

Site 23 Site 18

TD	ATM 2	3	5	7	9	10	11
2000						x	x
				x			x
				x			
	x			x			
1997		x			x		
1315	x	x					
1270	x					x	
1209				x	x		
704			x		x		
88	x				x		

classes (table 6.14).

There is much greater variability in the ability of two band combinations to separate the sedges from the elements of the heather community (table 6.14) although, as in the separation of these sites from the bracken stands, certain waveband combinations give a good separation at all the heather canopies.

The mature and the over-age stands are identified more clearly and consistently from the sedges than are the young stands. In the cases of sites 14 and 17 only three and two combinations respectively have TD values below 1600 (table 6.14). The waveband combinations which have poor discriminatory information are constant over all the over-age sites. The sedges stand is best separated from the young heather canopies in the near and mid- or thermal IR combinations which are also important for the overage stands, but there is a much greater range in discriminating ability between different waveband combinations (table 6.14).

The response of the _Eriophorum_ site relative to those of the young heather stands varies across the spectrum much more in the 1984 data than in the 1983 data. Thus few wavebands have sufficient discriminatory information to separate the _Eriophorum_ from all elements of the heather class. In the 1983 data ATM 3 was consistently critical in isolating the _Eriophorum_ class from all the heather sites. The results of section 6.4 suggests that this is also the case in the 1984 data. However ATM 3 gives consistently lower TD values than the IR combinations although it appears frequently amongst the best discriminators.

In summary the sedges class can be separated from all other elements of the moorland community with a minimum of spectral information, but the wavebands required to make these separations are more specific than those needed for the bracken canopy. The combination of near-IR with the mid-IR or thermal IR wavelengths gives the best results overall. The combinations which give poor separation between the sedges and the regenerating sites (sites 5 and 6) are also poor performers in the separation of the sedges from the heather classes.

The third main component of the moorlands, the exposed peat surface (site 4) is separated from its closest ecological neighbour, the partially vegetated sites in most two band combinations (TD>1977). The exceptions include the ATM 7,ATM 11 and ATM 7,ATM 10 combinations which are optimal for isolating the bracken and sedges classes, where TD=1882 and 1818 respectively for the separation of sites 4 and 5. The peat surface is separated from all elements of the heather group in any combination of two wavebands (TD > 1992 except for ATM 9,ATM 10, where TD=1969) These high TD values are expected from the data of section 6.5 and were also found in the 1983 data.

The separation of sites 5 and 6 (partially vegetated) from the full heather canopies is more variable (table 6.15). Site 6, which has a higher proportion of vegetation and a generally more variable response than site 5 can be separated from the over-age stands if the correct spectral information is available. It is however distinct from the mature stand in all wavebands. Site 5 is not distinguished clearly from the young heather sites 9 and 10 although it is separated from site 12 which is furthest from sites 5 and 6 in ecological terms. Site 6 is slightly better separated from sites 9 and 10. ATM 2, ATM3 and ATM 11 are important in specific cases. There is little pattern in the remaining combinations although the visible and mid-IR wavebands give high TD values most frequently and combinations of two IR bands perform badly. Adding further spectral information increases the number of waveband combinations which give acceptable levels of separation, but makes only minor differences to the maximum amount of discriminatory information.

In summary the major moorland canopies of bracken, sedges and the heather stands can be isolated by their spectral response.The exposed surface is separated from all fully vegetated stands in virtually any two band combination. In comparison with the 1983 data the level of spectral

Table 6.15 TD values: spectral separation of partially exposed surfaces and young or over-age heather canopies, August 1984 ATM data.

Site 5 Site 9

TD	ATM 2	3	5	7	9	10	11
1841	X		X				
1818	X			X			
1808	X					X	
1788	X						X
1786		X				X	
1206						X	X
1191					X	X	
1184				X	X		
1033			X		X		
1028				X		X	

Site 5 Site 10

TD	ATM 2	3	5	7	9	10	11
1842		X		X			
1837		X				X	
1818		X	X				
1816		X					X
1801		X			X		
1592					X	X	
1564				X	X		
1498			X	X			
1435			X		X		
1274				X		X	

Site 5 Site 12

TD	ATM 2	3	5	7	9	10	11
1993			X				X
1982		X					X
1958	X		X				
1949	X					X	
1938					X	X	
1716			X		X		
1705			X	X			
1346	X				X		
1312		X			X		
1291	X	X					

Site 5 Site 18

TD	ATM 2	3	5	7	9	10	11
1999	X		X				
	X			X			
		X		X			
1998		X	X				
1994				X			X
1920				X		X	
1902			X	X			
1897					X	X	
1888				X	X		
1721			X		X		

Site 6 Site 9

TD	ATM 2	3	5	7	9	10	11
1907		X				X	
1885			X			X	
1883	X		X				
1854		X		X			
1853	X	X					
1560					X		X
1505						X	X
1402				X			X
1389				X	X		
1264			X		X		

Site 6 Site 10

TD	ATM 2	3	5	7	9	10	11
1932		X				X	
1912		X			X		
1906		X				X	
1900	X	X					
1725	X		X				
1708				X		X	X
1704			X	X			
1652		X	X				
1606			X		X		

Site 6 Site 12

TD	ATM 2	3	5	7	9	10	11
1990			X				X
1980		X					X
1959					X		X
1955						X	X
1951				X		X	
1744			X		X		
1737			X	X			
1560		X			X		
1505	X				X		
1467	X	X					

Site 6 Site 18

TD	ATM 2	3	5	7	9	10	11
1969					X	X	
1907		X				X	
1885			X			X	
1883	X		X				
1854		X		X			
1560							
1505						X	X′
1402				X			X
1389				X	X		
1264			X		X		

separation between the vegetated classes is high and a greater number of waveband combinations give an acceptable result. This means that a subset of wavebands which optimally isolates two canopies is more likely to also isolate third and subsequent stands. ATM 7,ATM 11 or ATM 7,ATM 10 are amongst the best separators for all the fully vegetated sites, although other combinations also give acceptable and consistent results for smaller subsets. The ATM 7,ATM 11 and ATM 7,ATM 10 combinations are however amongst the poorest for making the important management distinction between the exposed peat surface and the partially vegetated regenerating sites. In this case the addition of any of the three visible bands to either combination brings them up to the performance of the best two band combinations. ATM 7,ATM 11 and ATM 7,ATM 10 also give poor results for the separation of the partially vegetated surfaces from some elements of the complete heather canopies. There is considerable variability and specificity in the wavebands which give good discrimination between these groups and this was also found in the 1983 data.

The second level of discrimination that is needed for moorland management is between the elements of the heather class. As discussed in section 6.5, the interband relationships and the structure of the spectral response at these sites are broadly similar to those in the 1983 data. Section 6.4 showed however that the detailed distribution of the heather stands by their spectral response, particularly in the visible bands, is slightly different at the two dates, although it is more or less constant across bands within a single acquisition.

The three young heather sites are not clearly separate in the TM bands although the data of section 6.4 showed that their response is not uniform in all bands. A combination of at least 4 wavebands, which includes ATM 11 and ATM 10, is needed to give an acceptable separation of sites 9 and 12. The maximum TD value for these sites, with 7 wavebands, is 1755 and a number of five-band combinations continue to give TD values under 1500 (table 6.16). The 7 band maxima for the separation of sites 9 and 10, and sites 10 and 12 are only 1379 and 1422 respectively. This is in marked contrast to the situation in the September 1983 data where these three sites could be separated clearly if ATM 3 or ATM 11 were used in the analysis. The 1984 data are however a much more accurate picture of the ecological similarity of these stands.

In contrast the TD values between pairs of the over-age stands are higher than the corresponding results in the 1983 data, although they are still below the levels associated with the differentiation of the major vegetation types (table 6.17). Figure 6.5 shows how the divergence between the over-age stands increases steadily with the addition of new spectral information. ATM 11 and ATM 10 are important in the discrimination of site 17 from sites 18 and 21 respectively. Five and six band combinations without ATM 11 or ATM 10 still give low TD values for these sites although an acceptable level of discrimination can be reached in four wavebands if they are included. Sites 18 and 21 are never clearly separated, the maximum TD value for these sites is 1629 when all 7 bands are included. The statistics of section 6.5 showed that these two classes have a similar response in all bands and this was also found in the 1983 data.

In management terms it is critical to separate the response of the young productive heather areas and the overage stands, as explained in chapter 3. In the 1983 data each element of each group had a slightly different spectral signature and there was no common combination of wavebands which separated all pairs of sites. This is also true of the 1984 data although the over-age stands have a uniform reponse in ATM 7 and the young heathers cannot be isolated in the ATM wavebands. Site 17 is generally well separated from the three young sites (table 6.18). The six band combinations suggest that no particular waveband is important but the best combinations include ATM 7 and this would be expected from the D norm values.

The open canopies of sites 18 and 21 are less clearly separated from the

Table 6.16 TD values: spectral separation of young heather canopies from each other, August 1984 ATM data.

Site 9 Site 10

TD	ATM 2	3	5	7	9	10	11
1322		x	x	x		x	x
1294		x	x	x	x		x
1289	x	x	x	x			x
1218		x	x	x	x	x	
1200			x	x	x	x	x
884	x			x	x	x	x
828	x	x			x	x	x
809	x		x		x	x	x

Site 9 Site 12

TD	ATM 2	3	5	7	9	10	11
1730		x	x	x		x	x
1712		x	x		x	x	x
1688	x	x	x	x			x
1685		x	x	x	x		x
1495		x	x	x	x	x	
1481				x	x	x	x
1473	x			x	x	x	x
1428	x	x	x	x	x		

Site 10 Site 12

TD	ATM 2	3	5	7	9	10	11
1348		x	x	x		x	
1255		x	x	x			x
1238			x	x		x	x
1233	x		x	x		x	
1216	x	x	x	x			

Table 6.17 TD values: spectral separation of over-age heather canopies from each other in combinations of six or seven wavebands.

Site 17 Site 18

TD	ATM 2	3	5	7	9	10	11
1961	X	X	X	X	X	X	X
1958		X	X	X	X	X	X
1947	X	X	X	X		X	X
1934	X	X	X		X	X	X
1929	X	X	X	X	X		X
1915	X	X		X	X	X	X
1883	X	X	X	X	X	X	
1874	X		X	X	X	X	X

Site 17 Site 21

TD	ATM 2	3	5	7	9	10	11
1953	X	X	X	X	X	X	X
1949	X	X	X	X		X	X
1948	X	X		X	X	X	X
1946		X	X	X	X	X	X
1928	X	X	X		X	X	X
1927	X		X	X	X	X	X
1922	X	X	X	X	X	X	
1679	X	X	X	X	X		X

Site 18 Site 21

TD	ATM 2	3	5	7	9	10	11
1629	X	X	X	X	X	X	X
1607	X	X	X	X		X	X
1598		X	X	X	X	X	X
1593	X	X	X	X	X	X	
1585	X		X	X	X	X	X
1408	X	X	X	X	X		X
1398	X	X		X	X	X	X
1110							

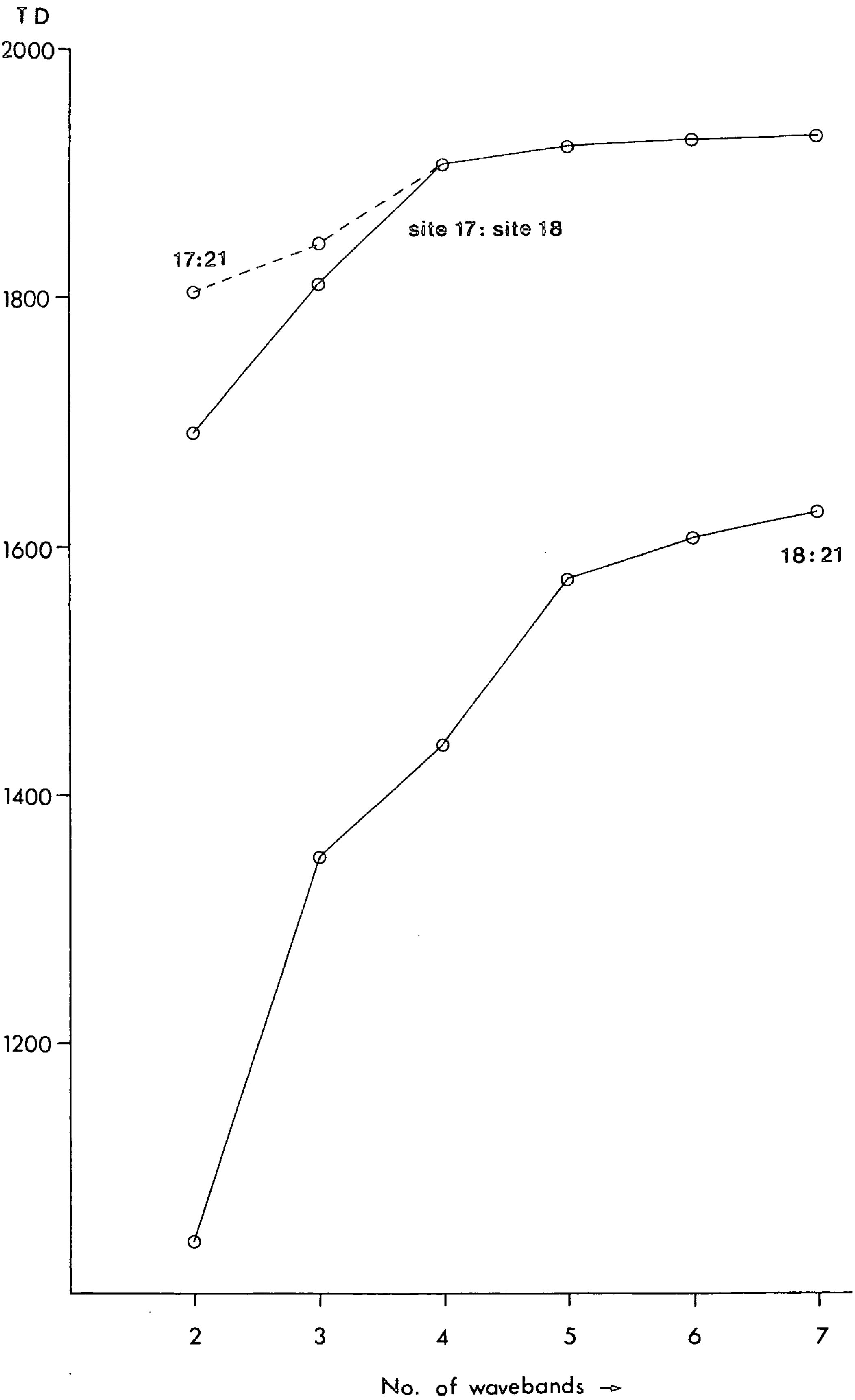


Figure 6.5 Increase in spectral separation between over-aged heather canopies (as measured by Transformed Divergence) with the addition of new wavebands, August 1984 ATM data.

ATM 5, ATM 7, ATM 11

Sites	TD	Sites	TD	Sites	TD
9 : 17	1999	10 : 17	1985	12 : 17	1999
9 : 18	1790	10 : 18	1345	12 : 18	1896
9 : 21	1790	10 : 18	1345	12 : 18	1896

ATM 2, ATM 5, ATM 7

Sites	TD	Sites	TD	Sites	TD
9 : 17	1971	10 : 17	1977	12 : 17	1999
9 : 18	1782	10 : 18	1509	12 : 18	1912
9 : 21	1282	10 : 21	1490	12 : 21	1851

ATM 3, ATM 5, ATM 10

Sites	TD	Sites	TD	Sites	TD
9 : 17	1913	10 : 17	1972	12 : 17	1995
9 : 18	1173	10 : 18	1274	12 : 18	1600
9 : 21	1510	10 : 21	1681	12 : 21	1910

ATM 2, ATM 7, ATM 10

Sites	TD	Sites	TD	Sites	TD
9 : 17	1992	10 : 17	1989	12 : 17	1999
9 : 18	1599	10 : 18	1590	12 : 18	1878
9 : 21	1325	10 : 21	1555	12 : 21	1838

ATM 7, ATM 11, ATM 10

Sites	TD	Sites	TD	Sites	TD
9 : 17	1999	10 : 17	1988	12 : 17	1999
9 : 18	1593	10 : 18	1441	12 : 18	1829
9 : 21	1683	10 : 21	1455	12 : 21	1837

Table 6.18 TD values, spectral separation of young and over-age heather canopies in three band combinations, August 1984 ATM data.

young heather areas. Three bands are needed to give a reasonable separation of site 12 from both the over-age sites, four or five bands are needed for site 9 and five or six for site 10 (figure 6.6). Similar amounts of spectral detail are needed for some pairs of sites in the 1983 data and the maximum levels of discrimination are the same. The five band combination which best discriminates the young heathers from the over-age stands is however common to all three young sites and the ATM 2,ATM 5,ATM 7 combination is optimal or near optimal in each three band case. There is however considerable variation in the performance of other three and four band combinations (table 6.18), as found in the 1983 data. The six band combinations indicate that ATM 7 is important in the separation of site 18 from all the young sites. ATM 5 is also important for the isolation of site 9 from site 18. There is no clear preference for any band for the separation of site 21 from the young heathers. In terms of this management task therefore the 1984 data show little improvement on the 1983 data.

The mature heather canopy and the area where heather is mixed with Eriophorum are similar to each other and lie in ecological terms between the young heather stands and the over-age canopies. The 7 band TD value between these sites is 1929, the corresponding value in 1983 was 1627. The increased separation is expected in the light of the greater discrimination between Eriophorum and heather in the 1984 data.

Section 6.4 showed that compared to the 1983 data, the distinctions between the mature heather and the over-age canopies are generally less clear in individual wavebands of the 1984 data and this is confirmed by the TD values. The mature canopy (site 14) is separated from the open canopies of sites 18 and 21 in the ATM 10,ATM 11 combination; all other combinations which include ATM 11 also give a high TD value for site 18. There is however considerable variation in the performance of different pairs of wavebands and this range is greater than that for the 1983 data (table 6.19). The mature canopy is closest in ecological terms to the closed canopy of site 17 and the maximum two band separation of these sites

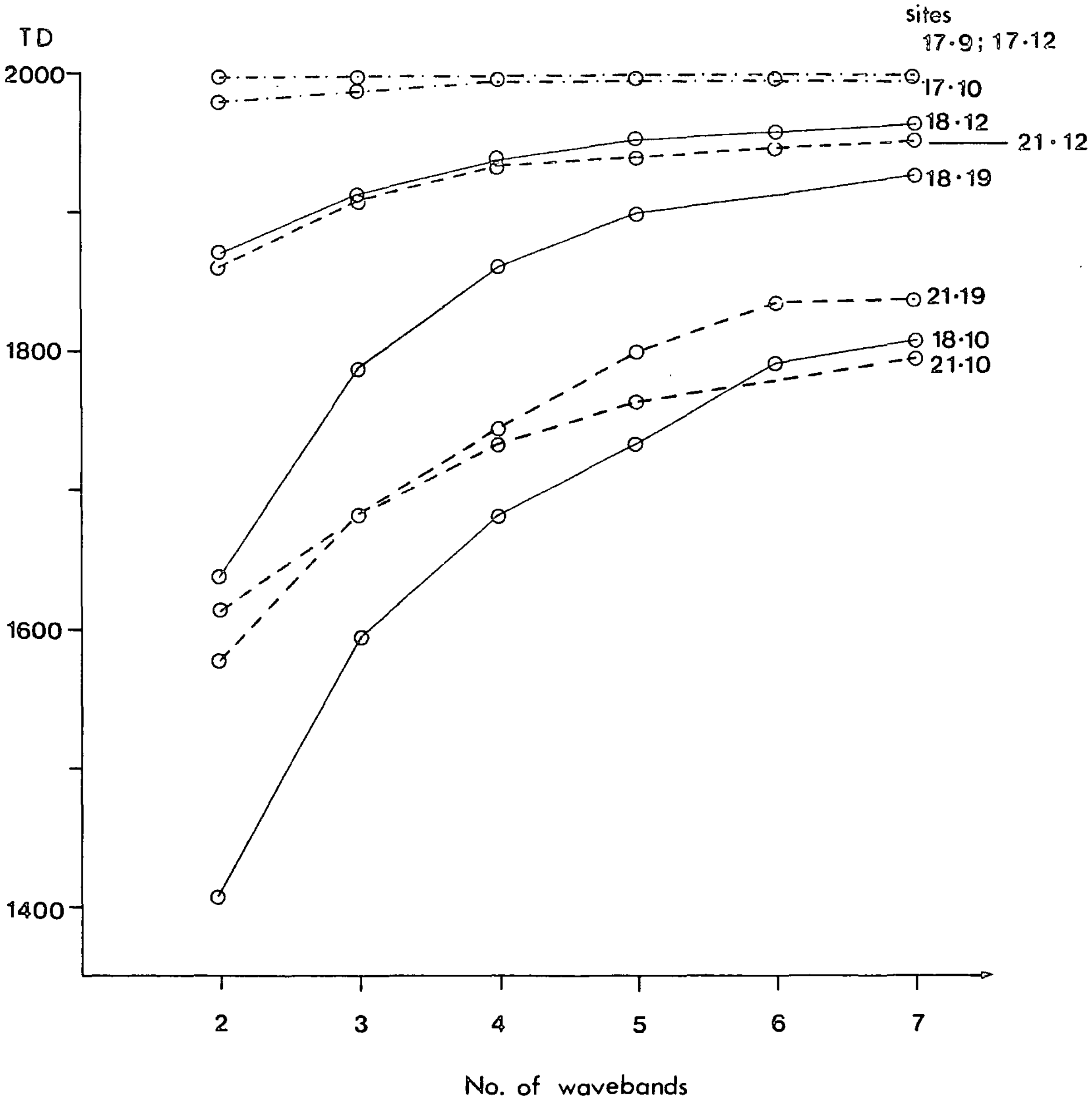


Figure 6.6 Increase in spectral separation between young and over-aged heather canopies (as measured by Transformed Divergence) with the addition of new wavebands.

Table 6.19 TD values: spectral separation of mature heather and young or over-age heather canopies.

Site 14 Site 9

TD	ATM 2	3	5	7	9	10	11
2000						X	X
1999							
1917					X	X	
1371	X					X	
1238	X	X					
862	X			X			
786			X	X			
489	X		X				

Site 14 Site 10

TD	ATM 2	3	5	7	9	10	11
1999						X	X
1994			X				X
1992				X			X
1987					X		X
1986		X					X
1347	X				X		
1173	X	X					
1145			X	X			
967	X		X				
952	X			X			

Site 14 Site 12

TD	ATM 2	3	5	7	9	10	11
1999						X	X
1990				X			X
1986		X					X
1985					X		X
1984			X				X
1639	X				X		
1603			X	X			
1459	X			X			
1442	X		X				
1366	X					X	

Site 14 Site 18

TD	ATM 2	3	5	7	9	10	11
1999						X	X
1989				X			X
1984	X						X
1983			X				X
1966		X					X
1170		X			X		
731	X			X			
486	X	X					
353		X	X				
254	X		X				

Site 14 Site 21

TD	ATM 2	3	5	7	9	10	11
1991						X	X
1763			X				X
1730	X					X	
1710	X					X	
1698		X				X	
784			X		X		
746	X		X				
651		X			X		
642			X	X			
629	X		X				

Site 14 Site 17

TD	ATM 2	3	5	7	9	10	11
1772	X						X
1699				X			X
1674			X				X
1602	X			X			
1559				X	X		
1018		X					X
573					X		X
509		X				X	
403					X	X	
196		X			X		

is low at TD=1772. The TD value increases steadily with the addition of new spectral information so that the optimal 4 and 5 band combinations approach the levels of separation attained at the other sites. As in the 1983 data, the eventual clear separation of the over-age canopies from the mature stands is useful for management but the apparent differences in canopy structure do not seem large enough to explain the degree of spectral separation.

In management terms it is less critical but still important to isolate the mature canopies from the areas of young or building heather growth, in fact they can be distinguished clearly (TD>1999) in a number of two band combinations (table 6.19). The best results occur when ATM 11 is included although the 6 band combinations show that this is only a marginal dependence. In the 1983 data the separation of the two full canopies (sites 10 and 12) from the mature stand was lower in absolute terms although ATM 11 was still important. Five wavebands are needed in the 1983 data to match the discriminating power of the best two band combinations in 1984. The level of separation of sites 9 and 14 is similar for both dates and all five band combinations give an acceptable separation for the three young sites. In all cases the range of TD values for the separation of the mature and the young heather canopies is not as great as that for the separation of the mature and the over-age stands and the levels of discrimination are generally higher.

The wavebands required to isolate the mature heather from the young heather are similar to those needed to separate the mature and the over-age stands (table 6.19). ATM 10,ATM 11 and ATM 5,ATM 11 give good results for the young sites and two of the over-age sites and ATM 5,ATM 11 is also near optimal for the third over-age site, site 17, (ATM 5,ATM 11 TD=1674, maximum TD=1772), but ATM 10,ATM 11 returns a TD value of 1161 for these sites.

The differences between the two dates in the type and level of discrimination within the heather class is less than that for the major moorland communities. In most cases the levels of discrimination in the 1984 data are slightly higher than those in the 1983 data and there is less evidence for the importance of a specific waveband or spectral region, i.e., more waveband combinations give an acceptable separation of a range of canopies. This does not hold for all cases however and, for example, if noise from redundant spectral information is to be avoided, a number of different classifications would be needed to isolate the elements of the over-age heather stands from all other canopies.

6.6 Summary

In the 1983 data the canopies of bracken, Eriophorum, heathers and exposed surfaces could be distinguished from each other in two band combinations and in most cases a number of such combinations gave acceptable results. ATM 5, ATM 3 and ATM 7 were clearly optimal for distinguishing the sedges from the bracken, heather and exposed surfaces respectively. Both the exposed peat surface and the partially vegetated areas were equally well separated from the fully vegetated stands. There was however a wide variation in the discriminating ability of two band combinations and there were a number of cases, documented in chapter 5, where wavebands which were optimal or near optimal for one group of canopies were poor discriminators of another pair or group.

In the 1984 data all the major vegetated canopies can be separated from each other with a minimum of spectral information. The exposed peat surface is also clearly distinguished from all vegetated sites in all waveband combinations. The maximum levels of separation in two bands are similar to those of the 1983 data but the overall levels of separation are higher, that is, more two band combinations give TD values over 1600 for each pair or group of canopies. This means that the inclusion of specific wavebands is less critical and a number of combinations will give acceptable results for several groups of canopies. The only clear discrepancy is ATM 5,ATM 7 which has uniformly high discrimination between all sites except for bracken and sedges where the TD value falls to 1055. ATM 7,ATM 11, ATM 7,ATM 10 and ATM 2,ATM 7 are consistently good performers amongst the vegetated sites. The regenerating sites are not so clearly separated from the full heather canopies and along with most other combinations, ATM 7,ATM 11 and ATM 11,ATM 10 give poor results for some pairs of sites from these groups.

The general increase in discriminating power in the 1984 data also applies to the more detailed delimitation of the heather communities although the change is less marked. In the 1984 data there are fewer occasions where a specific waveband or spectral region can be identified as crucial to the separation of a pair or group of canopies although they do occur. The variation in response within the over-age classes and the young heather found in the 1983 data persists in the 1984 data and there is overlap between the elements of each class. There is considerable variation in the wavebands needed to separate all elements of these classes. The stand of mixed Calluna and Eriophorum is more clearly separated from the pure heather stand and this is expected from the distribution of the heather and sedges stands as shown in section 6.4. In comparison, the mature heather canopy has a similar spectral response to the over-age stands in the 1984 data and site 17 in particular is not well separated from the mature stand. This distinction was made clearly in the 1983 data.

Although the general distribution of the two data sets is similar there are therefore differences between them in both the levels of discrimination between elements of the moorland community and in the type, amount and specificity of the spectral information needed to make these distinctions. In practical terms the differences are sufficient to have a bearing on the practical aspects of data selection as well as the accuracy attainable in automated classifications. This suggests that the original hypothesis is false and that temporal resolution, or rather the precise state of the community at the time of imaging, has practical implications for mapping vegetation in the moorland environment.

It should be noted that a part of the general increase in separation in the 1984 data may be due to artefacts of the scanner and the sensing process such as different illumination and gain settings. Although this should be miminal it has not been possible to quantify the magnitude of the effects for these data sets as simultaneous ground radiometer data were not available. Similarly although every effort was made to locate precisely the same test sites in each data set minor location errors may exist. This means that a change in response may be due to the inclusion of different proportions of canopy elements in the sample rather than an actual spectral change in the target. Again this is thought to be minimal.

The two data sets were acquired at approximately the same time of year, although under slightly different conditions of antecedent moisture (Brown, pers. comm.). If the differences in response between the two dates comes only from change in the targets over time (as opposed to location errors or change due to the sensing process) they are therefore the result of fairly subtle changes in the state of the vegetation and the substrate, although those changes in the bracken and sedges stands could be due to phenological factors as the data were collected close to the time of canopy change. For the other stands this suggests that short term fluctuations in environmental conditions could be important in determining the amount and type of discriminating information in the data. These may be localised and are clearly less easy to predict than directional phenological change.

Detailed information on the precise state of the vegetation and the substrate at the two dates is not available. Qualitative judgments recorded in the field suggest that the visible condition of the canopy and substrate were similar at the two dates. There is clearly considerable scope for further controlled work here, preferably by taking detailed field or laboratory measurements of radiance from semi-natural canopies simultaneously with information on canopy features over time.

6.8 May 1984 data.

Analysis of the limited May data set should allow some clarification of these rather confused results. With the qualifications outlined in section 6.2, the May data are expected to differ from the August and the September acquisition in both the amount and type of discriminating information they hold. Changes are expected at both levels of management. Those at the upper level, which affect the separation of the major communities of bracken, sedges and heathers, are expected to be greater than the corresponding changes within the Calluna dominated areas.

The test sites in the May data, listed in table 6.20, span two flight lines and, for the reasons described in section 6.2, are compared directly only with those on the same flight line. The discussion of the spectral separation of these sites is therefore less detailed than the corresponding descriptions of the autumn data.

6.8.1 Discrimination in single wavebands.

The distribution and separation of the test sites in the May data is similar in all three visible bands (table 6.21) and a close match to that in the autumn data, especially the 1984 data set. The Dnorm matrices for the three visible bands are very similar (table 6.21). The few exceptions occur in flight line 4, where the separation of sites 4 and 24 from a number of the vegetated stands varies from band to band.

There is a generally clear division in all three bands between the vegetated and the wholly or partly exposed sites. In flight line 4 however the response of the exposed peat surface is low and not well separated from a number of the vegetated sites. In flight line 5 the pattern reverts to that of the autumn data and the response of the peat surface is similar to that of the partially vegetated sites. Compared to the autumn data the response of the new burn sites is low in all three bands and a better match to the ground radiometer readings. This is expected as these data were acquired closer to the time of the spring burn.

Within the vegetated areas the pattern of response in the heather class in

Flight line 4

Site number	Description
4	Exposed peat surface
8	Partially vegetated peat surface
9	Young heather (incomplete canopy)
17 - 19, 21	Over-age heather
23	Eriophorum
24	New burn

Flight line 5

Site number	Description
4	Exposed peat surface
5,6	Partially vegetated peat surface
10,12	Young heather (complete canopy)
14	Mature heather
21	Over-age heather
24	New burn

Table 6.20 Test sites used in analysis of May data. For full description see table 6.2.

Flight line 4

Site	ATM 2 $\bar{x}$	c.v.	ATM 3 $\bar{x}$	c.v.	ATM 5 $\bar{x}$	c.v.
4	65.95	3.946	53.83	4.545	55.82	4.996
8	76.51	4.460	64.65	5.317	67.68	4.945
9	64.84	5.615	53.57	7.269	56.21	6.620
17	61.44	2.242	50.54	3.067	53.57	3.272
18	61.79	4.172	49.45	6.161	51.45	6.872
19	57.41	1.359	45.94	2.059	48.65	2.317
21	60.02	1.603	47.61	1.702	50.69	1.804
23	59.72	6.038	48.02	8.117	50.17	7.524
24	73.10	2.521	58.82	3.429	60.07	4.046

Flight line 5

Site	ATM 2 $\bar{x}$	c.v.	ATM 3 $\bar{x}$	c.v.	ATM 5 $\bar{x}$	c.v.
4	69.60	10.635	60.09	12.659	67.80	13.190
5	68.75	5.219	58.48	5.710	59.90	6.029
6	68.28	4.030	58.96	4.158	61.79	4.237
10	53.93	4.042	46.05	4.277	48.67	3.751
12	50.34	1.644	41.55	2.253	44.83	2.648
14	52.37	1.232	43.99	1.800	45.87	2.331
21	49.37	2.158	40.60	2.762	43.14	2.527
23	55.87	4.091	48.36	5.971	51.13	7.039
24	62.27	1.770	51.72	2.348	52.80	2.766

Table 6.21a Summary descriptive statistics of response at test sites, ATM 2, ATM 3, ATM 5, May 1984 data.

Table 6.21b: Dnorm values: spectral separation of test sites ATM2, ATM3, ATM5, May 1984.

Flight line 4

ATM 2

site	8	9	17	18	19	21	23	24
4	1.93	0.06	0.50	0.69	1.83	1.39	0.86	0.81
8	-	1.62	2.77	2.36	4.25	3.99	2.46	1.32
9		-	0.48	0.66	1.56	1.19	0.81	0.63
17			-	0.40	1.71	1.08	0.62	1.55
18				-	0.60	0.17	0.18	1.45
19					-	1.00	0.31	3.21
21						-	0.11	2.81
23							-	1.60

ATM 3

site	8	9	17	18	19	21	23	24
4	1.76	0.18	1.14	0.80	2.53	1.67	1.00	1.61
9		-	0.68	0.49	1.68	1.05	0.71	1.51
17			-	0.09	1.87	0.61	0.35	3.63
18				-	1.30	0.50	0.34	2.56
19					-	1.50	0.53	5.98
21						-	0.07	4.66
23							-	2.46

ATM 5

site	8	9	17	18	19	21	23	24
4	1.84	0.04	0.82	2.32	0.80	1.91	0.91	1.12
8	-	1.51	2.83	2.34	4.27	4.01	2.27	1.07
9		-	0.56	0.59	1.58	1.27	0.71	0.89
17			-	0.24	1.84	1.24	0.46	2.32
18				-	0.88	0.48	0.21	1.85
19					-	0.95	0.43	4.35
21						-	0.09	3.97
23							-	1.83

Flight line 5

ATM 2

site	5	6	10	12	14	21	22	24
4	0.14	0.11	1.06	1.52	1.36	1.58	0.89	0.49
5	-	0.08	2.57	4.17	3.87	4.16	2.19	1.38
6		-	2.91	5.01	4.68	4.95	2.46	1.56
10			-	1.19	0.55	1.41	0.43	2.54
12				-	1.38	0.51	1.78	6.18
14					-	1.75	1.19	5.66
21						-	1.94	5.95
22							-	1.89

ATM 3

site	5	6	10	12	14	21	22	24
4	0.05	0.09	0.98	1.49	1.28	1.55	0.74	0.55
5	-	0.08	2.34	3.96	3.51	4.01	1.63	1.48
6		-	2.92	5.14	4.61	5.14	1.99	1.98
10			-	1.55	0.74	1.76	0.48	1.78
12				-	1.41	0.46	1.78	4.73
14					-	1.77	1.19	3.85
21						-	1.93	4.76
22							-	0.82

ATM 5

site	5	6	10	12	14	21	22	24
4	0.26	0.15	1.10	1.43	1.37	1.57	0.82	0.82
5	-	0.96	2.07	3.14	3.00	3.56	1.22	1.40
6		-	2.95	4.46	4.32	5.03	1.71	2.20
10			-	1.27	0.97	1.90	0.45	1.26
12				-	0.46	0.74	1.32	3.01
14					-	1.26	1.13	2.74
21						-	1.70	3.79
22							-	0.33

the May data is broadly similar to that in the autumn data. The Eriophorum site however shows a rather different relative response between the two flight lines. In flight line 4 it has a response which is generally similar to that of the over-age heathers. In flight line 5 it is closer to that of the young heather canopy. This degree of variation from sample sites within the same canopy at the same date suggests either that this variation has been undersampled in the other data sets, or that the May data are even less reliable than stated in section 6.2. The variation between the two flight lines is however considerably less than that between the autumn and the spring data. In the September data set the response of the sedges was closely aligned with that of the partially exposed sites. In the August 1984 data it showed greater variation from band to band, but was generally similar in response to the young heathers.

The pattern of response in the mid-IR bands is very similar to that in the visible bands (table 6.22) and the positive correlation between these two spectral regions is consistent across almost all sites in both flight lines. This relationship was also present in the 1983 data and to a lesser extent in the 1984 data set. ATM 10 in particular clarifies the separation of the fully vegetated stands from the areas of partial cover and the exposed peat sites. In ATM 11 the variation in response at each site is low and is not consistently correlated with any other band. This waveband contains no new discriminatory information for the vegetated stands. The new burn sites are however clearly isolated from all other sites by their high response in ATM 11. The response of the exposed peat site in flight line 5 drops below that of the partially vegetated sites to match the situation in flight line 4.

ATM 7 departs from the pattern of the other bands and the picture here is rather confusing. Both new burn sites have a low response, as expected. In the autumn data the response over all other sites increases in rough proportion to biomass and the heather stands keep their positions relative to each other. In flight line 5 in the May data all sites except 4 and 6,

Flight line 4

Site	ATM 7 $\bar{x}$	c.v.	ATM 9 $\bar{x}$	c.v.	ATM 10 $\bar{x}$	c.v.	ATM 11 $\bar{x}$	c.v.
4	27.33	7.963	55.67	8.638	71.43	11.081	149.81	6.503
8	30.56	7.741	65.97	6.636	91.88	10.270	157.07	4.766
9	28.91	5.958	52.53	9.411	65.12	11.837	135.35	5.307
17	25.75	2.772	46.10	3.136	58.03	3.033	131.86	1.946
18	24.84	6.494	46.83	9.082	60.20	10.339	140.58	5.626
19	25.77	4.218	43.43	3.644	53.54	2.835	131.74	1.922
21	26.79	4.109	44.44	3.448	53.37	2.922	133.97	2.195
23	25.05	7.266	45.39	11.526	57.05	14.201	137.62	3.868
24	20.99	4.764	57.71	4.643	89.03	4.120	196.63	3.589

Flight line 5

Site	ATM 7 $\bar{x}$	c.v.	ATM 9 $\bar{x}$	c.v.	ATM 10 $\bar{x}$	c.v.	ATM 11 $\bar{x}$	c.v.
4	29.10	6.245	74.58	11.647	106.75	14.987	162.18	7.931
5	24.47	4.278	63.71	6.739	98.12	8.727	187.01	5.146
6	26.16	7.912	65.54	5.201	98.66	7.267	179.00	4.028
10	27.47	3.500	48.46	5.855	58.50	9.196	147.18	3.040
12	27.13	4.229	41.08	3.460	46.93	3.614	132.36	2.634
14	26.27	4.217	44.30	3.772	53.01	3.210	140.45	2.190
21	24.31	4.315	40.50	3.522	48.75	3.719	131.62	1.875
23	26.69	5.933	47.85	7.292	59.57	7.643	137.93	2.698
24	19.84	3.139	54.98	3.829	89.20	4.176	199.16	3.641

Table 6.22a Summary descriptive statistics of response at test sites, ATM 7, ATM 9, ATM 10, ATM 11, May 1984 data.

Table 6.22b Dnorm values: spectral separation of test sites, ATM 7, ATM 10, ATM 11, May 1984

Flight line 4

ATM 7

site	4	8	9	17	18	19	21	23
4	0.71	0.41	0.55	0.66	0.48	0.16	0.57	2.00
8	-	0.40	1.56	1.44	1.39	1.09	1.32	2.84
9		-	1.30	1.22	1.12	0.75	1.09	2.91
17			-	0.39	0.01	0.57	0.28	2.78
18				-	0.34	0.72	0.06	1.47
19					-	0.47	0.25	2.29
21						-	0.60	2.76
23							-	1.44

ATM 10

site	4	8	9	17	18	19	21	23
4	0.42	0.85	1.46	0.52	1.47	1.25	0.81	2.79
8	-	1.48	2.51	1.07	2.53	2.22	1.52	2.72
9		-	0.36	0.35	0.37	0.14	0.18	4.30
17			-	0.83	0.02	0.38	0.73	6.73
18				-	0.85	0.61	0.22	3.75
19					-	0.41	0.75	6.77
21						-	0.44	6.27
23							-	4.77

ATM 11

site	4	8	9	17	18	19	21	23
4	1.18	0.40	1.38	0.79	1.90	1.91	0.90	1.52
8	-	1.56	3.02	2.02	3.50	3.50	1.99	0.22
9		-	0.75	0.35	1.26	1.27	0.51	2.10
17			-	0.27	1.37	1.40	0.10	5.71
18				-	0.86	0.88	0.22	2.91
19					-	0.05	0.37	6.84
21						-	0.38	6.82
23							-	2.72

Flight line 5

ATM 7

site	5	6	10	12	14	21	22	24
4	1.40	0.73	0.50	0.58	0.84	1.44	0.62	3.21
5	-	0.60	0.48	0.33	0.04	0.66	0.16	2.66
6		-	1.79	1.21	0.84	0.07	0.85	2.77
10			-	0.16	0.58	1.57	0.30	4.81
12				-	0.38	1.28	0.16	4.12
14					-	0.91	0.16	3.71
21						-	2.02	2.67
22							-	3.10

ATM 10

site	5	6	10	12	14	21	22	24
4	0.20	0.22	1.25	1.94	1.68	1.85	1.24	0.12
5	-	0.03	2.84	4.99	4.39	4.76	2.94	0.73
6		-	2.76	4.40	3.79	4.94	3.79	1.37
10			-	1.86	0.88	2.23	1.12	4.44
12				-	1.23	0.12	0.77	6.22
14					-	1.59	0.37	5.68
21						-	1.02	6.95
22							-	5.58

ATM 11

site	5	6	10	12	14	21	22	24
4	1.71	1.53	0.13	1.07	0.57	1.19	0.71	2.54
5	-	0.45	2.83	4.17	3.67	4.58	3.78	0.72
6		-	2.76	4.40	3.79	4.94	3.79	1.37
10			-	1.86	0.88	2.23	1.12	4.44
12				-	1.23	0.12	0.77	6.22
14					-	1.59	0.88	5.68
21						-	2.23	6.95
22							-	5.58

which have an unexpectedly high response, follow this pattern. The response of the over-age site is therefore lower than that of the regenerating and exposed sites and there is little differentiation of the stands in between. A parallel situation occurs in flight line 4 where the response of sites 4 and 8 is higher than expected.

There seems to be no clear explanation for the change in the relative reponse of the exposed and the partly exposed sites and particularly the variation in response within this group in the May data. In management terms however it does not add new discriminatory information to the data set, apart from the separation of the over-age stand and site 12 of young heather in flight line 5. These are separated more clearly in ATM 7 than in any other band and this was also true in the August 1984 data.

In summary, with the exception of the Eriophorum stand and the confusion in the near-IR band, the distribution of the test sites in the May data is similar to that of the autumn data sets. The results imply that there will be little change in the amount of discrimination that is possible between the heather canopies in these data. At the upper level of management however the Eriophorum stand will not be isolated from the heather stands.

6.8.2 Multispectral separation

The TD values for this data set (summarised in table 6.23) show that the exposed peat surface (site 4) can be separated from the two neighbouring regenerating surfaces in two or three wavebands although the levels of separation are lower than those in the autumn data.

The fully and partly exposed sites are clearly separated (TD > 1920 for all two band combinations) from the young, mature and over-age heathers sampled on both flight lines. This consistently good separation is an improvement on both the August and the September data sets.

The sample of the Eriophorum stand in flight line 5 can be separated from all other partially and fully vegetated stands if the correct wavebands are used (table 6.23). As suggested in section 6.8.1 the corresponding sample

Table 6.23 TD values: spectral separation of selected test sites within each flight line, May 1984 ATM data.

Site 4 Site 6 (line 4)

TD	ATM 2	3	5	7	9	10	11
1882					x	x	
1860		x	x				
1805					x		x
1798	x				x		
1786			x			x	
1440	x			x			
1346			x				x
1026	x	x					
1018		x					x
934	x						x

Site 4 Site 5 (line 4)

TD	ATM 2	3	5	7	9	10	11
1990	x		x				
1973		x	x				
1914					x	x	
1913	x				x		
1906				x		x	
1423	x	x					
1404			x				x
1270			x		x		
916	x						x
670		x					x

Site 4 Site 8 (line 5)

TD	ATM 2	3	5	7	9	10	11
1892			x	x	x		
1856			x		x	x	
1850			x	x		x	
1845			x		x	x	
1807	x			x		x	
973				x	x	x	
858		x	x		x		
818		x	x	x			
772		x	x				x
672		x	x			x	

Site 9 Site 8 (line 4)

TD	ATM 2	3	5	7	9	10	11
1736			x			x	
1727				x		x	
1683		x				x	
1678	x					x	
1606			x				x
1510							
1491							
1477							
1410							
1401							

Site 23 Site 8 (line 4)

TD	ATM 2	3	5	7	9	10	11
1922			x	x			
1906	x			x			
1881			x			x	
1861	x					x	
1845			x				x
1015		x			x		
989	x		x				
572	x	x					
298	x				x		
						x	x

Site 23 Site 9 (line 4)

TD	ATM 2	3	5	7	9	10	11
1999	x			x			
1992			x	x			
	x						x
1990	x	x					
1989		x		x			
657		x					x
268				x		x	
233			x		x		
132	x		x				
66		x			x		

Site 23 Site 18 (line 4)

TD	ATM 2	3	5	7	9	10	11
1947	x	x					
1897			x	x			
1838	x						x
1740		x		x			
1718	x			x			
899				x		x	
849				x	x		
645				x			x
440					x	x	
384	x		x				

Site 9 Site 21 (line 4)

TD	ATM 2	3	5	7	9	10	11
1998		x					x
		x	x				
1997	x	x					
	x				x		
1994	x		x				
			x				x
1897					x	x	
1789			x	x			
1779			x				x
1420				x	x		
1088				x		x	

Table 6.23 cont.

Site 10 Site 12 (line 5)

TD ATM	2	3	5	7	9	10	11
1971						x	x
1966			x				x
1963	x						x
1959					x		x
1957		x					x
1798		x	x				
1726				x		x	
1684	x		x				
1648	x			x			
1515			x	x			

Site 10 Site 14 (line 5)

TD ATM	2	3	5	7	9	10	11
1723				x			x
1665						x	x
1624			x				x
1565		x					x
1554					x		x
1355			x			x	
1288		x	x				
1200							
1077				x		x	
1027			x		x		

Site 10 Site 21 (line 5)

TD ATM	2	3	5	7	9	10	11
1996		x			x		
1994			x			x	
1993		x				x	
1992				x	x		
1989	x					x	
						x	x
1852	x						x
1849	x		x				
1830	x			x			
1813		x	x				
1808	x	x					

Site 12 Site 14 (line 5)

TD ATM	2	3	5	7	9	10	11
1886				x			x
1884			x				x
1796						x	x
1771		x		x			
1330		x			x		
1179			x			x	
1153			x	x			
1084				x		x	
1032			x		x		

Site 12 Site 21 (line 5)

TD ATM	2	3	5	7	9	10	11
1466			x				x
1335	x						x
1304				x			x
1261		x		x			
1250		x					x
423						x	x
401	x				x		
331		x				x	
290	x	x					
111					x	x	

Site 14 Site 21 (line 5)

TD ATM	2	3	5	7	9	10	11
2000	x						x
	x	x					
	x				x		
1999	x					x	
	x			x			
793					x	x	
704				x		x	
517				x	x		
500				x			x
329					x		x

in flight line 4 is not easily separable from the heather stands.

The spectral overlap between elements of the heather class found in the autumn data is also present in the May data. Table 6.24 compares the separation of selected canopies over the three dates. In flight line 5 the two examples of young heather,. sites 10 and 12, can be separated quite clearly (TD> 1956) in two bands if ATM 11 is included (table 6.23). This is similar to the 1983 data where the discriminatory information in ATM 11 is also important although the maximum TD value was lower at 1884. In comparison the maximum separation of these sites in the August 1984 data is 1422 when all seven bands are used.

In the May data site 10 is also well separated from the over-age stand in two wavebands (maximum TD=1996 for ATM 3,ATM 9), but three or four bands are needed for its clear separation from the mature stand (maximum TD=1833 for ATM 7,ATM 11,ATM 10). Site 12 is more clearly distinct from the mature stand, in wavebands similar to those optimal for site 10 (TD=1886 for ATM 7,ATM 11), but it is less clearly separated from the over-age stand even when ATM 7 is included (maximum two band TD=1466 for ATM 5,ATM 11). The third young heather stand (site 9, present on flight line 4, is clearly separated from the mature and the over-age sites (TD > 1998) although there is little clear pattern in the wavebands required for these separations.

In the August data both young canopies can be separated from the mature stand if ATM 11 is included but are confused with the open canopies of the over-age stand. A similar situation arises in the September data although the level of separation between the young and the mature sites is closer to that in the May data. The maximum distinction of the mature and the over-age stands is similar at all dates.

Table 6.24 shows that the maximum levels of separation between the young and the mature heather sites are similar in the May 1984 and the September 1983 data. The May data contain different information on the relative distribution of the young heather canopies and one of the over-age stands, although the results, where site 10 is isolated and site 12 is not, is not

	September 1983 TD	September 1983 bands	May 1984 TD	May 1984 bands	August 1984 TD	August 1984 bands
Sites 10 : 12	1824	ATM 10,11	1971	ATM 10,11	1422	all 7 bands
Sites 10 : 14	1726	ATM 7,10	1723	ATM 7,11	1999	ATM 10,11 or ATM 3,11
Sites 12 : 14	1842	ATM 7,11	1886	ATM 7,11	1999	ATM 10,11
Sites 10 : 21	1522	ATM 10,11	1996	ATM 3, 9	1615	ATM 3, 5
Sites 12 : 21	1765	ATM 9,10	1466	ATM 5,11	1861	ATM 3, 7
Sites 14 : 21	1947	ATM 9,10	2000	ATM 2,11 or ATM 2, 3 or ATM 2, 9	1991	ATM 10,11

Table 6.24 TD values: spectral separation of heather canopies in September 1983, May 1984 and August 1984 data.

particularly helpful in management terms. In addition, the sites of over-age heather on flight line 4 can all be separated from each other in two or three wavebands which suggests that a continuous intermingling of young and over-age sites is the most likely situation.

6.9 Summary and Conclusions

From the data available it has not been possible to refute the hypothesis that temporal resolution is unimportant in the moorland environment.

There are differences between the three data sets in the levels of separation that can be made between sites and in the combination of wavebands needed to attain these levels. The greatest differences, between both the two autumn data sets and the autumn and spring acquisitions are at the upper level of management, which aims to distinguish the heather, bracken, sedges and exposed surfaces. Changes in the relative response of the Eriophorum and the bracken stands over time are the main source of the changes in discriminating information. It should be noted however that the unexplained discrepancies between flight lines in the May data sets makes it difficult to attach confidence to the conclusions involving this data set.

Although the autumn data sets were acquired at the same calendar date it is possible that at least some of the differences in response are due to seasonal changes that are not immediately apparent in the canopy. The differences in response are however greater than expected and, with further differences that cannot be tied to phenological change, suggest that short term fluctuation in conditions within a season may also be important in deciding the amount and type of discriminatory information in the data.

Within the heather canopy however there is generally little clear or directional variation across the three data sets, which suggests that temporal resolution is not an important variable in selecting data for this level of moorland management. Despite the inherent difficulties of using a statistical surrogate to measure classification accuracy, the similarity of the waveband combinations which separate some elements of the heather class at each date suggests that spectral resolution, for the TM wavebands, is important at this level of management.

Clearly a multi-temporal data set with greater radiometric and geometric accuracy would allow a more rigorous analysis of this topic. The results presented in this chapter however suggest that temporal resolution is important in the moorland environment if sedges and bracken are to be isolated from each other and from the remaining moorland cover types. It is less important, for the ATM wavebands, if the main purpose is to differentiate cover types within the heather-dominated areas.

Chapter Seven: Re-examination of data sets used in chapters 4 - 6, the importance of spatial resolution.

7.1 Introduction

The results of chapters 5 and 6 show that the maximum separation of most pairs or groups of canopies in the ATM data can be retained in a subset of wavebands by rejecting wavebands which have inappropriate or duplicate discriminatory information. The success with which the subset of wavebands performs depends on the care with which its elements are selected and, for some canopies, this may also depend on the state of the plant and the environment at the time of acquisition.

As described in previous chapters however the spectral separation of canopies is closely linked to the spatial resolution of the sensor with which the data are collected. The variability in the spectral response of a target will tend to decrease as the integration area of the sensor is increased, although the magnitude of this effect will depend on the spectral heterogeneity of the canopy elements.

For any target therefore there will be an optimum spatial resolution at which its spatial extent can be mapped accurately and its spectral response is relatively uniform. At this point the amount of variance that is held between classes will be at its maximum and the targets will show their greatest spectral separation. This chapter examines how far defining and selecting such an appropriate spatial resolution is an effective form of data reduction - comparable to reducing the spectral and temporal dimensions of the data.

Two hypotheses are tested in particular. The first is that pertinent spectral data do not yield useful information without an appropriate spatial resolution. This examines the most immediate effect of spatial resolution on data quality, which is to set an approximate lower limit on the size of target that can be distinguished.

The results of chapters 5 and 6 show that most of the moorland canopies have at least some separation in the Landsat MSS wavebands. The hypothesis suggests however that the relatively coarse resolution of this Landsat sensor is a limit on its utility as a data source in moorland management. The amount of information in the Landsat MSS data and the degree to which it is constrained and enhanced by the sensor's spatial resolution is discussed in section 7.3.

The spatial resolution of both the ATM data described in chapters 5 and 6 and further ATM data acquired as a simulation of the SPOT HRV multi-spectral sensor (see chapter 2 and section 7.2) examined in this chapter are a closer match to the spatial periodicity of the patchwork within the heather moorland. Analysis of these data in sections 7.4 - 7.6 concentrates on the critical management tasks within the heather moorland and tests the second hypothesis, that a decrease in spatial resolution causes a decrease in the variation of spectral response at each site. As noted previously this change in the distribution of variance in the data is expected to cause an increase in spectral separation between cover types. On this basis the discriminatory information in the data introduced in this chapter is expected to exceed that in the comparable wavebands of the ATM data of chapters 5 and 6. The data are examined further to determine whether the magnitude of this effect, if present, compensates for the loss of the mid- and thermal IR bands in the SPOT HRV data.

Section 7.7 summarises the results from this chapter and the relative importance of spatial, spectral and temporal resolution in this environment. This is expanded upon in chapter 8, which discusses how data from each satellite system might best be brought together into a GIS for moorland management and the way in which such a system should develop to operational status.

7.2 Data

The data sets examined in this chapter are those used in previous chapters together with Landsat MSS data acquired in May 1977 and two ATM data sets flown in May and July 1984. These were acquired as part of the National Remote Sensing Centre's SPOT simulation campaign, using a Daedalus AADS 1268 scanner as described in chapter 2. The SPOT HRV bands are simulated by combining Daedalus wavebands where necessary. To avoid confusion in terminology these data are referred to as airborne SPOT HRV data and the wavebands are referred to as XS1, XS2 and XS3. As noted in chapter 2 the data are analysed as DN values and not converted to radiance. The data of chapters 5 and 6 continue to be referred to as ATM data.

The results of chapters 5 and 6 suggest that there will be some change in the spectral response of the moorland communities between these data sets due to episodic and seasonal change in the condition of the vegetation and the environment. The differences will lie mainly in the response of the Eriophorum and bracken stands relative to all other sites. The detailed analysis in this chapter however concentrates on sites within the heather moorland, where the effects of temporal change are expected to be minimal.

7.3 Landsat MSS data

Water bodies and areas of arable land, bracken and heather moor were located in the MSS data and the spectral response of these sites, as relative DN, is summarised in table 7.1. As in the 1983 ground radiometer readings the MSS wavebands form a feature space which is basically 2-dimensional in structure. The two visible bands are positively correlated to each other (r ranges from 0.53 to 0.93) and a stronger and more consistent relationship exists between the two near-IR bands ($r > 0.91$ except for the heather canopy, where $r=0.46$). Figure 7.1 shows that the major cover types can be isolated by their response in the MSS wavebands although some of the arable areas have a response similar to elements of the natural vegetation. It is not possible to separate coniferous

Site		MSS 4 Green	MSS 5 Red	MSS 6 Near-IR 1	MSS 7 Near-IR 2
Water	$\bar{x}$	13.04	28.89	4.72	2.73
	c.v.	14.206	8.886	49.780	66.781
Pasture		30.01	39.20	129.33	123.91
		25.668	12.000	17.354	14.786
Arable		39.06	46.35	122.61	123.46
		33.178	17.939	23.788	17.930
Bracken		51.26	44.05	80.52	81.93
		22.973	14.315	20.025	19.720
Heather moor		24.51	29.25	45.63	43.25
		26.668	14.032	11.553	15.231
Conifers		16.75	26.59	43.45	40.70
		20.420	10.200	14.223	18.478

Correlation matrices

Pasture

	G	R	IR 1
R	.79		
IR 1	-.64	-.44	
IR 2	-.56	-.28	.91

Agriculture

	G	R	IR 1
R	.92		
IR 1	-.68	-.60	
IR 2	-.55	-.42	.92

Bracken

	G	R	IR 1
R	.92		
IR 1	.71	.74	
IR 2	.79	.84	.93

Heather moor

	G	R	IR 1
R	.59		
IR 1	.47	.32	
IR 2	.37	.39	.46

Conifers

	G	R	IR 1
R	.53		
IR 1	.42	.52	
IR 2	.45	.58	.94

Table 7.1 Summary statistics of response for major moorland communities in Landsat MSS data

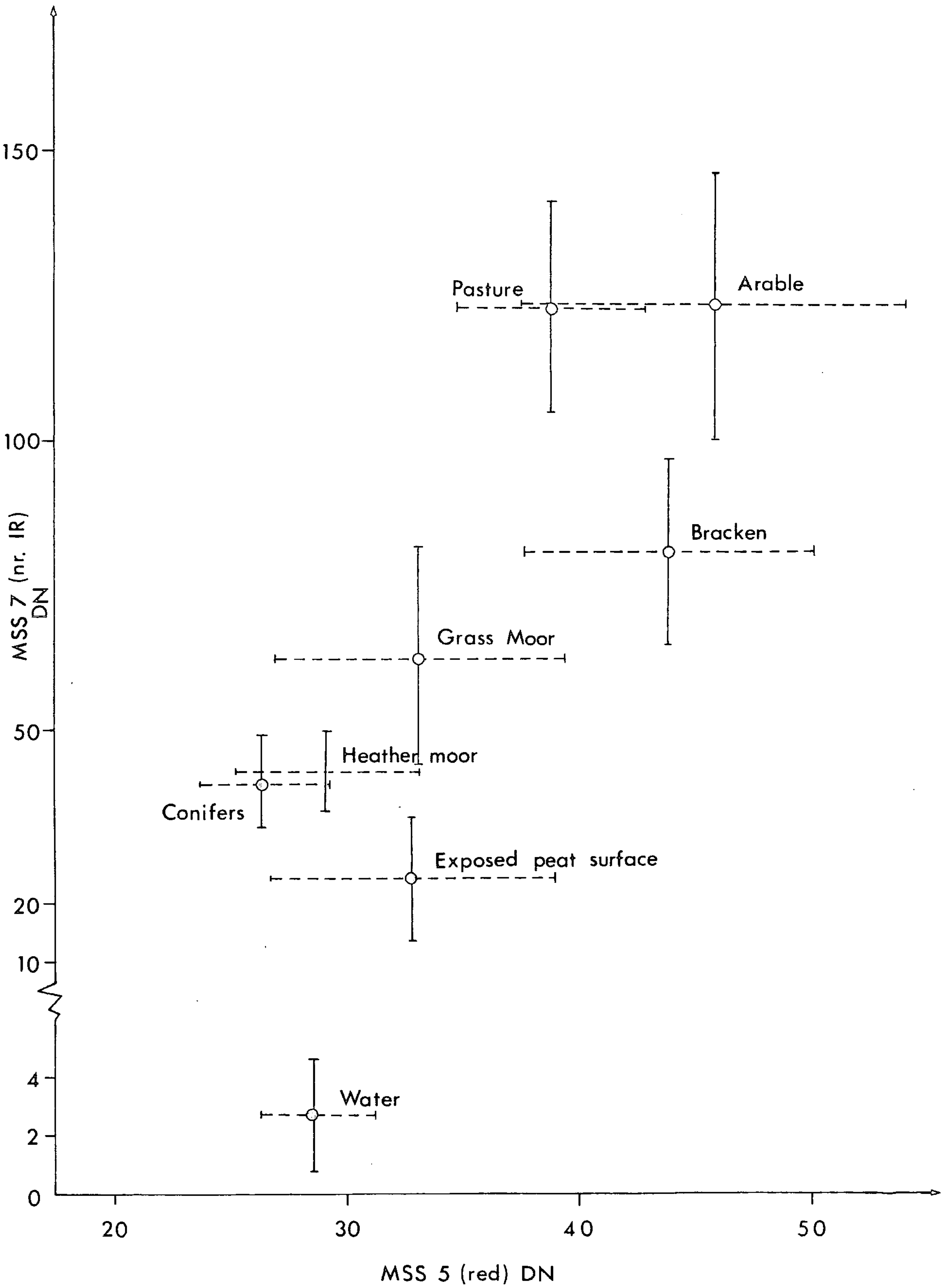


Figure 7.1 Spectral response of major communities in the feature space defined by the red and near-IR wavebands of the Landsat MSS

plantations from the heather moor in the MSS data, a result also found and discussed extensively by Betts (1984).

The areas of heather, bracken and arable land are well separated in the visible wavebands but the response of the heather moor overlaps that of the agricultural targets in the adjacent valleys, which are mainly pasture. It is important to isolate these two groups if the amount of moorland which is improved for pasture is to be monitored, and this distinction is available in the near-IR bands. Similarly the bracken stands are confused with elements of the more arable type of farming found in the Vale of York in the visible bands but the two groups are more clearly identified in the near-IR. The residual confusion between these two classes is unimportant in the North Yorks Moors but may be so in areas with less clearly defined vegetation limits. Table 7.2 summarises the statistical separation of these classes in each waveband and in the full feature-space. The tables confirm that the near-IR holds most of the discriminatory information for these communities.

Although the major cover types are spectrally distinct in the MSS data, the spatial resolution of the sensor is such that the boundaries between them can be located with an accuracy of only 80-160m (1-2 pixels) at best. In practical terms this lack of spatial precision does not preclude the use of MSS data for monitoring the reclamation of moorland for agriculture, as this process involves a dramatic change of land cover over relatively large contiguous blocks of land. Precise boundary information may also be available from other sources. However the identification of land previously reclaimed and now reverting to moorland will however be hampered by this relatively coarse resolution, as small patches revert at different rates and to different types of cover. Similarly, where bracken is invading heather the boundary between the two is diffuse and the spread and die back of bracken in general does not occur in discrete units. The value of MSS data in bracken control is therefore confined to the reconnaissance level, where the aim is to identify and locate rather than to measure.

Dnorm values MSS 5

	2	3	4	5
1	0.44	1.71	1.60	0.05
2		1.94	1.79	0.43
3			0.16	1.54
4				2.11

Dnorm values MSS 7

	2	3	4	5
1	2.66	4.41	5.04	6.17
2		1.74	2.79	0.15
3			1.08	1.86
4				3.89

TD values: 2 visible bands

	2	3	4	5
1	713	2000	2000	2000
2		1999	1993	848
3			1298	1579
4				1704

TD values: 2 near-IR bands

	2	3	4	5
1	2000	2000	2000	2000
2		1907	2000	54
3			1208	1952
4				2000

TD values: four bands

	2	3	4	5
1	2000	2000	2000	2000
2		2000	2000	970
3			1682	1979
4				2000

1 water
2 conifers
3 bracken
4 arable
5 heather moorland

Table 7.2 Spectral separation of major communities in Landsat MSS data

Further test areas were extracted from the area of heather moor to determine what, if any, information was available on the distribution of vegetation within the moorland area. The spectral characteristics of these sites and a brief description of their vegetation are given in table 7.3 and figure 7.1. The results show that the bare peat surface and the low-lying grass moors have some spectral separation from the areas dominated by Calluna, which have a very similar mean response in all bands. The variance at each Calluna-dominated site increases in rough proportion to the amount of variation in vegetation at that site (table 7.3) but there is no clear spectral breakdown of the heather moor into its components of partially vegetated sites, established heathers and pockets of sedges. The results of chapters 5 and 6 and the fact that the grass moors and the burnt site can be separated where they have sufficient spatial extent suggest that the limit on further sub-division is spatial rather than spectral.

In summary the spectral and spatial characteristics of the Landsat MSS data allow the heather moor to be isolated from the surrounding bracken. Agricultural areas and water bodies can also be distinguished. The spatial periodicity of the different cover types within the heather moorland is higher than the resolution of the sensor and is not recorded at a level that is useful for management. In addition the boundaries of the major cover types cannot be positioned with sufficient accuracy in the raw MSS data at anything other than a reconnaissance level.

At a detailed level of analysis the spatial resolution of the MSS data is therefore a constraint on their practical utility as it is too coarse to provide precise information at either level of management. However, the major communities, particularly the heather areas, appear as homogeneous targets in the MSS data. A finer spatial resolution, which would allow clearer delimitation of the major communities would, by disaggregating the moorland response, cause some spectral confusion between elements of the

Site		MSS 4 Green	MSS 5 Red	MSS 6 Near-IR 1	MSS 7 Near-IR 2
Fylingdales	$\bar{x}$	16.75	25.59	43.45	40.70
Moor	c.v.	20.423	10.200	14.223	18.478
Calluna (over-aged) monoculture					
Moorsholm Moor		28.23	33.37	62.00	62.01
low-lying grass moor		38.90	19.473	30.929	31.030
Glaisdale Moor		26.06	31.07	25.60	24.39
peat surface exposed after fire		32.346	19.934	33.722	42.606
Wheeldale Moor		24.42	29.20	45.19	42.56
Calluna patchwork		18.850	11.424	8.446	10.883
Danby High Moor		28.13	30.78	47.40	45.90
Calluna patchwork		34.554	19.327	24.166	28.786

Table 7.3 Summary statistics of response for sample sites within the heather moorland, Landsat MSS data

moorland mosaic and the surrounding areas of bracken and agriculture. The relatively coarse resolution of the Landsat MSS is therefore an advantage at the small-scale reconnaissance level and, in a GIS approach to moorland management, would provide initial targetting information on the distribution of water bodies, heather moor, bracken, grass moor and large areas of exposed peat caused by catastrophic fire.

7.4 Airborne SPOT HRV data

The airborne SPOT HRV data carry similar spectral information to the MSS data but at a spatial resolution which allows individual elements of the moorland patchwork to be identified. This section examines the spectral response and statistical separation of the moorland canopies in the airborne SPOT HRV data before comparing them to the ATM data of chapters 5 and 6 in section 7.5. The clear spectral distinction between bracken and moorland present in the MSS data is lost in the airborne SPOT data, especially the July acquisition, as the averaged moorland response is broken into its constituent parts. The separation is better in the May data, where the response of the bracken litter has a greater spectral contrast with the heather canopies.

The area over which the data were collected is large enough to include some of the bracken sites used in the clearance programme introduced in chapter 3. The sites support untouched stands with different levels of vigour and cleared sites with different levels of regrowth. The possibilities of breaking down the bracken class into these groups, as described in chapter 3, is examined briefly in this section to estimate the potential of remotely sensed data for managing bracken encroachment.

7.4.1 Heather moorland

The wider area covered by the airborne SPOT HRV data allowed approximately 90 sites to be located from ground survey and those which could be located in the central strip of the imagery at the two dates are used in this analysis (see foldout list of test sites, Appendix 2). The larger sample will give a much better indication of the natural variation in response from stand to stand within a cover class than was possible in the ATM data.

The distribution of the sample sites in the visible bands of the July airborne SPOT HRV data is similar to that in the corresponding bands of both the September 1983 and the August 1984 ATM data. The areas of complete heather canopy have a relatively low and uniform response in both XS1 and XS2. Within this group the mature and degenerate stands as a group have the lowest and most similar response. The stands of young vigorous growth have a slightly higher, more variable response. There is considerable overlap between these two classes as a whole although individual sites are separated (tables 7.4, 7.5). XS2 gives a slightly better discrimination between most sites.

As expected from the results of chapters 5 and 6 the response from the partly vegetated sites is much higher than that of the established stands and individual sites differ widely in their response. In comparison with the ATM data however, the internal variance of each regenerating site is not much above that of the young heather sites. They are therefore well separated as a body from the vegetated canopies in both the visible bands (table 7.5), in contrast to the ATM data where some confusion existed between the regenerating sites and the stands of young heather.

The response of the new burn sites falls within the limits of the partly exposed surfaces and this was also found in the August 1984 ATM data. In XS1 they group together at the lower limit of response of the partly exposed sites and have little overlap with individual regenerating sites, although such overlap does exist in XS2 (table 7.4). The three regenerating sites which have a lower radiance than the new burns in XS1 have vegetation cover of 65%, 80% and 20% respectively, although the last also has a dark peat substrate. It is likely that other partly exposed sites will have responses which overlap the response of the new burns. They are therefore unlikely to be recognised consistently from the

Site	XS 1		XS 2		XS 3		
	$\bar{x}$	c.v.	$\bar{x}$	c.v.	$\bar{x}$	c.v.	
4	54.24	9.257	53.76	9.645	80.27	6.192	over-age/
8	54.39	2.533	53.77	1.893	85.00	8.705	mature
43	55.72	2.465	54.50	1.764	91.19	5.957	Calluna
85	52.83	3.032	52.50	2.333	76.00	4.633	
91	50.25	3.807	49.75	3.748	76.75	5.126	
19	54.75	4.498	53.92	4.652	81.38	5.279	mature/
39	53.33	2.228	52.56	2.186	84.83	8.406	building
87	53.29	2.289	52.21	2.013	80.96	3.612	Calluna
26	55.67	11.994	54.58	11.724	79.17	5.718	
17	75.81	4.399	76.31	4.056	72.73	5.879	young/
21	67.04	6.788	67.00	6.700	80.21	7.370	regenerating
88	71.50	2.617	71.79	2.742	65.93	11.994	
74	74.32	2.539	74.84	2.517	66.11	7.971	
40	71.12	5.297	71.40	5.722	82.22	13.165	
36	63.85	3.494	65.85	3.825	56.45	5.986	new burns
42	63.00	1.697	65.00	2.397	53.87	2.613	

Table 7.4 Summary statistics of response for heather canopies, airborne SPOT HRV data, July 1984

XS 1

	8	43	85	91	19	39	87	26	17	21	88	74	40	36	42
4	0.02	0.23	0.21	0.58	0.07	0.15	0.15	0.12	2.58	1.40	2.50	2.91	1.92	1.46	1.46
8	-	0.48	0.52	1.26	0.09	0.41	0.42	0.16	4.54	2.24	5.27	6.10	1.62	3.21	3.68
43		-	0.97	1.66	0.25	0.93	0.94	0.01	4.27	2.01	4.86	5.70	1.32	2.76	3.12
85			-	0.73	0.47	0.18	0.16	0.34	4.65	2.41	5.38	6.16	3.41	3.47	3.97
91				-	1.03	0.99	0.97	0.63	4.87	2.69	5.62	6.33	3.67	3.91	4.44
19					-	0.39	0.40	0.10	3.63	1.84	3.87	4.50	2.63	2.26	2.41
39						-	0.02	0.30	4.97	2.49	5.94	6.82	3.59	3.81	4.50
87							-	0.30	4.94	2.49	5.89	6.77	3.58	3.79	4.45
26								-	2.01	1.07	1.85	2.18	1.48	0.99	0.96
17									-	1.04	0.83	0.29	0.66	2.44	2.98
21										-	0.25	0.82	0.42	0.62	0.84
88											-	0.75	0.07	2.22	3.00
74												-	0.57	3.03	3.97
40													-	1.36	1.74
36														-	0.34

XS 2

	8	43	85	91	19	39	87	26	17	21	88	74	40	36	42
4	0.00	0.12	0.20	0.57	0.02	0.19	0.25	0.07	2.72	0.37	2.52	3.00	1.90	1.88	1.87
8	-	0.33	0.57	1.40	0.04	0.56	0.76	0.11	5.48	2.40	6.03	7.39	3.45	5.35	6.05
43		-	0.84	1.57	0.16	0.84	1.03	0.01	5.12	2.21	5.52	6.79	3.22	4.72	5.25
85			-	0.89	0.38	0.02	0.13	0.27	5.51	2.54	6.04	7.31	3.56	5.42	6.06
91				-	0.95	0.93	0.84	0.58	5.35	2.71	5.75	6.78	3.64	5.19	5.64
19					-	0.37	0.48	0.07	4.72	4.00	3.99	4.82	2.65	3.18	3.31
39						-	0.16	0.27	5.60	2.56	6.17	7.47	2.09	5.57	6.26
87							-	0.32	5.81	2.67	6.48	7.85	3.74	5.96	6.77
26								-	2.29	1.14	2.06	2.46	1.60	1.47	1.44
17									-	1.23	0.89	0.30	0.68	2.41	2.88
21										-	0.74	1.24	0.51	0.20	0.38
88											-	0.80	0.06	1.85	2.42
74												-	0.58	2.93	3.68
40													-	1.04	1.30
36														-	0.41

XS 3

	8	43	85	91	19	39	87	26	17	21	88	74	40	36	42
4	0.44	1.05	0.50	1.07	0.16	0.38	0.04	0.12	0.82	0.01	1.11	1.38	0.12	0.95	3.14
8	-	0.55	0.97	1.47	0.32	0.01	0.51	0.57	1.22	0.41	1.39	1.72	0.17	1.11	3.37
43		-	1.70	2.18	0.97	0.51	1.27	1.21	1.90	0.97	1.89	2.34	0.55	1.36	4.20
85			-	0.70	0.73	0.83	0.71	0.39	0.42	0.45	0.88	1.13	0.43	0.83	3.18
91				-	1.33	1.27	1.44	0.99	0.24	0.96	0.41	0.50	0.78	0.60	2.29
19					-	0.27	0.16	0.29	1.05	0.15	1.30	1.63	0.03	1.04	3.60
39						-	0.42	0.49	1.06	0.35	1.26	1.51	0.15	1.05	2.93
87							-	0.19	1.09	0.04	1.35	1.77	0.12	1.05	4.20
26								-	0.73	0.10	1.06	1.33	0.20	0.93	3.17
17									-	0.73	0.56	0.69	0.63	0.67	2.44
21										-	1.03	1.26	0.12	0.92	2.81
88											-	0.01	1.40	0.34	1.06
74												-	1.00	0.38	1.40
40													-	0.84	1.99
36														-	0.11

Table 7.5a Dnorm values: Spectral separation of heather canopies, airborne SPOT HRV data July 1984. See table 7.4 for identification of sites.

XS 1, XS 2

	8	43	85	91	19	39	87	26	17	21	74	40	36	42
4	1580	1463	1764	1014	376	1430	1754	2000	1983	1303	1900	1768	1867	1998
8	-	253	748	1538	612	437	996	2000	2000	1999	2000	2000	1999	1999
43		-	995	1659	494	779	1016	2000	2000	1999	2000	1999	1999	1999
85			-	1240	921	425	859	2000	2000	1999	2000	2000	2000	2000
91				-	900	964	1025	1999	2000	1957	2000	1999	1999	1999
19					-	522	905	1999	1999	1817	1999	1978	1965	1979
39						-	246	1999	2000	1999	2000	2000	1999	1999
87							-	1999	2000	2000	2000	2000	2000	2000
26								-	2000	2000	2000	2000	2000	2000
17									-	1378	312	560	1857	2000
21										-	1683	579	1600	1900
74											-	864	1944	2000
40												-	1481	1900
36													-	800

XS 2, XS 3

	8	43	85	91	19	39	87	26	17	21	74	40	36	42
4	1743	1817	1998	1701	1962	1864	1624	100	1990	124	1999	1861	1999	2000
8	-	312	1380	1586	737	429	933	1924	2000	1999	2000	2000	2000	2000
43		-	1859	1773	1195	645	1647	1951	2000	1999	2000	2000	2000	2000
85			-	1652	1130	1685	1267	1987	2000	2000	2000	2000	2000	2000
91				-	827	1269	1136	1337	2000	1997	2000	1999	2000	2000
19					-	1155	843	652	1999	1895	2000	1995	1999	2000
39						-	819	1973	2000	2000	2000	2000	2000	2000
87							-	1872	2000	1999	2000	2000	2000	2000
26								-	1985	1109	1999	1843	1999	2000
17									-	1467	903	1271	1922	2000
21										-	1768	574	1984	2000
74											-	1315	1968	1999
40												-	1992	2000
36													-	1834

XS 1, XS 2, XS 3

	8	43	85	91	19	39	87	26	17	21	74	40	36	42
4	1771	1906	1999	1116	531	1906	1796	2000	1991	1374	1999	1876	1999	2000
8	-	471	1731	1636	875	618	1344	2000	2000	2000	2000	2000	2000	2000
43		-	1969	1836	1379	931	1735	2000	2000	2000	2000	2000	2000	2000
85			-	1941	1663	1902	1804	2000	2000	2000	2000	2000	2000	2000
91				-	923	1389	1257	1999	2000	1999	2000	1999	2000	2000
19					-	1276	1059	1999	1999	1904	2000	1996	1999	2000
39						-	1053	2000	2000	2000	2000	2000	2000	2000
87							-	1999	2000	1999	2000	2000	2000	2000
26								-	2000	2000	2000	2000	2000	2000
17									-	1611	1031	1305	1956	2000
21										-	1846	983	1996	2000
74											-	1466	1993	2000
40												-	1993	2000
36														1895

Table 7.5b TD values: Spectral separation of heather canopies, airborne SPOT HRV data, July 1984

regenerating sites in these bands.

Apart from the subtle difference in the positioning of the new burn sites the ordering and separation of the sample sites is virtually identical in XS1 and XS2 and the two wavebands are highly correlated at all sites. This duplication is acknowledged by Begni (1982), as noted in chapter 2, and has been found in other studies of vegetated surfaces in the airborne SPOT HRV bands (see SPOT Simulations Applications Handbook, Amer. Soc. Photogramm. 1984).

The near-IR band XS3 however contains different information. In the ATM data sets the general sequence of response in the visible bands is reversed in the near-IR band so that the exposed sites have a low response and the vegetated areas a high one. In general this is also the case in the airborne SPOT HRV data. The fully vegetated heather stands have the highest response. Compared to the visible bands the response within the heather class is variable and the internal variation at each site is also higher. This is also the case in both the September 1983 and the August 1984 ATM data. There is no apparent grouping within the heather class, the mature/over-age heather stands and the young canopies share the same range of response in this waveband.

Most of the partially vegetated sites have a low response in the near-IR but some have a response similar to that of the full heather canopies. This was also indicated in the smaller number of samples in the ATM data and is apparent in the imagery where much of the patchwork appearance of the moorland is lost in the near-IR band. There is however a rather better separation of the new burn sites at the lower limit of response although their statistical separation from the other sites is often lower than that in the visible bands.

Figure 7.2 shows the distribution of a sample of the test sites in the feature space defined by XS2 and XS3. The total data set has a 2-dimensional structure of visible and near-IR response similar to that found in the Landsat MSS data. The information in figure 7.2 is therefore

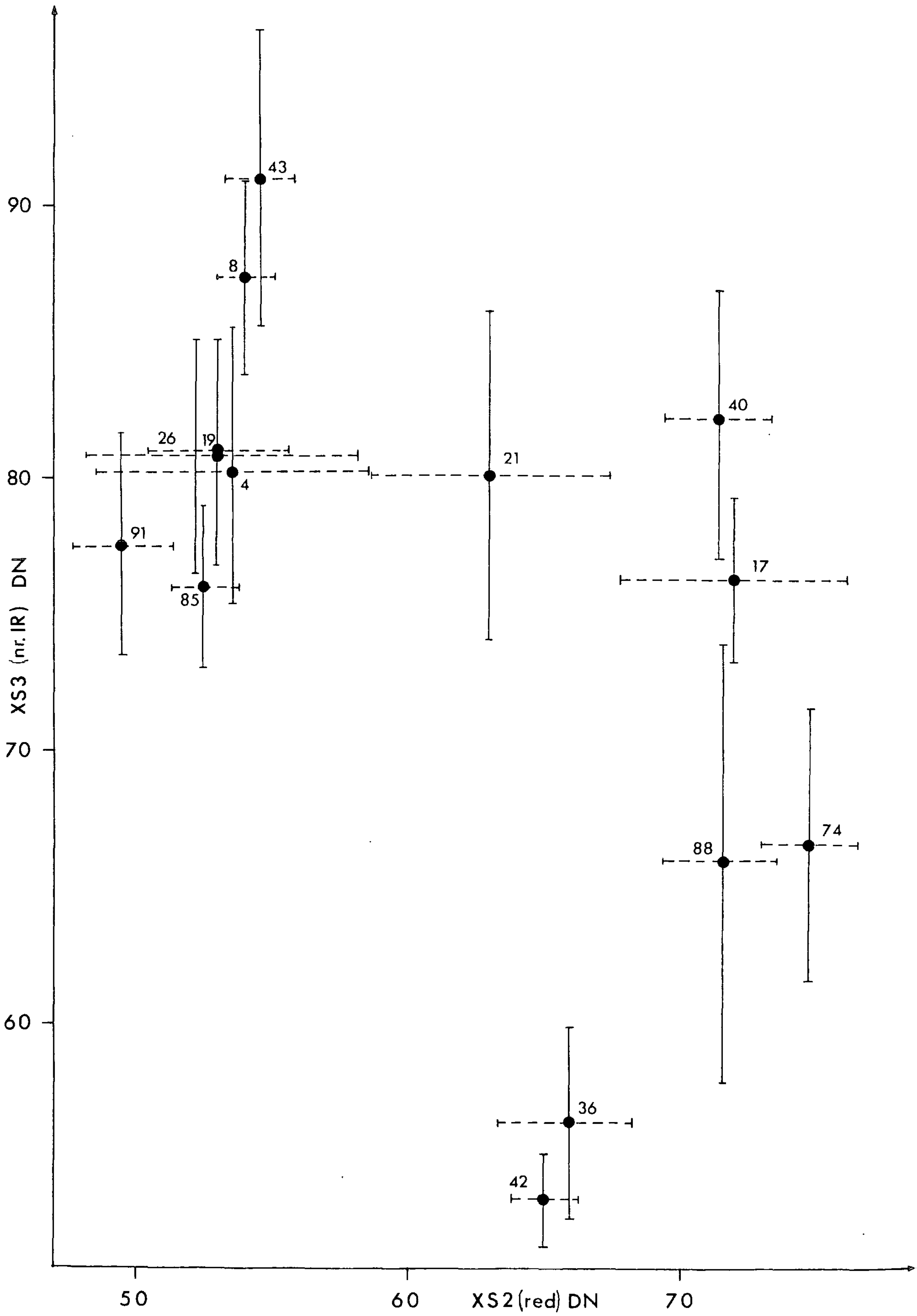


Figure 7.2 The spectral response of moorland test sites in the feature space defined by the airborne SPOT HRV wavebands, July 1984

an almost complete picture of the discriminatory information available from the SPOT data for these sites at this date. It is reasonable to assume that this is the type of discrimination that would be possible from the Landsat MSS if it had a finer spatial resolution.

Table 7.5 summarises the maximum levels of separation possible between some of the test sites as measured by the Dnorm and the TD value. The general pattern of discrimination is similar in the three sets of TD measurements and, with the exception of one or two sites, there is little difference in discriminating power between the XS2:XS3 and XS1:XS2:XS3 combinations. The matrices show that the clearest divisions are between the fully vegetated areas and the partially or wholly exposed sites. There is little separation between the young and the over-age heather stands and in a number of cases stands in the two heather classes are more clearly separated from stands within their own class than they are from sites in the second class.

The spectral response of the same sites in the May data is summarised in table 7.6. The two visible bands are again highly correlated although compared to the July data the similarities in their distribution are less marked. The general pattern of response in both bands is similar to that in the corresponding bands of the July data, i.e. response increases with decreasing green vegetation.

The division between the vegetated and the partially or fully exposed sites is not as immediately clear as in the visible bands of the July data, although table 7.7 shows that for the sample sites the overall level of discrimination is similar. The over-age and mature sites have a low and, particularly in XS1, uniform response (figure 7.3). The response of the young heathers is however more variable and a number of these sites have a response similar to the partially vegetated sites in both the visible bands. Two partially vegetated areas have a response within the range of the established canopies. Compared to the July data there is however a

Site	XS 1		XS 2		XS 3		
	$\bar{x}$	c.v.	$\bar{x}$	c.v.	$\bar{x}$	c.v.	
4	24.26	1.828	27.00	0.000	23.74	4.375	over-age/
8	26.23	6.583	28.39	7.315	27.26	9.888	mature
43	25.10	3.199	27.20	4.027	24.87	2.041	heather
85	24.57	7.742	25.57	8.096	22.71	3.328	
91	23.50	2.869	24.00	0.000	22.92	2.917	
19	25.03	5.251	26.90	5.994	23.83	4.100	mature/
39	24.90	5.503	26.60	5.660	23.50	3.009	building
87	28.00	5.144	30.14	6.105	27.79	10.656	heather
26	23.52	2.889	24.71	5.298	23.33	3.130	
17	24.15	7.608	25.26	9.640	23.89	4.066	young/
21	33.62	2.739	37.33	3.527	27.62	6.525	regenerating
88	32.78	6.892	35.30	7.992	24.18	8.267	
74	35.29	3.153	39.14	2.731	25.00	2.309	
40	33.44	4.329	37.13	3.322	26.63	6.167	
36	26.58	4.028	28.47	3.178	18.95	14.767	new burns
42	26.87	2.766	29.13	1.773	18.00	2.100	

Table 7.6 Summary statistics of response for heather canopies, airborne SPOT HRV data May 1984

XS 1

	4	8	43	91	19	39	87	26	17	21	88	40	36	42
4	0.91	0.68	0.13	0.68	0.44	0.35	1.99	0.65	4.10	7.45	7.47	10.3	4.10	1.72
8	-	0.45	0.46	1.14	0.39	0.43	0.56	1.12	2.07	3.10	2.70	3.32	0.15	0.23
43		-	0.20	1.08	0.03	0.09	1.29	1.06	3.23	5.41	5.12	6.67	1.05	0.94
85			-	0.42	0.15	0.10	1.03	0.41	2.42	3.49	3.16	3.77	0.80	0.77
91				-	0.77	0.68	2.13	0.02	4.03	6.85	6.77	8.86	2.40	1.93
19					-	0.05	1.08	0.76	2.72	4.20	3.85	4.77	0.80	0.77
39						-	1.10	0.67	2.72	4.16	3.81	4.70	0.85	0.81
87							-	2.11	1.71	2.72	2.23	2.88	0.69	0.45
26								-	4.01	6.81	6.72	8.79	2.38	1.91
17									-	0.29	0.33	0.08	2.88	2.32
21										-	1.02	0.72	5.13	3.79
88											-	0.58	4.75	3.34
74												-	6.51	4.33
40													-	0.17
36														
42														

XS 2

	8	43	85	91	19	39	87	26	17	21	88	40	36	42
4	0.67	0.18	0.69	3.00	0.06	0.26	1.71	1.75	4.24	7.87	7.46	8.21	2.42	2.36
8	-	0.37	0.68	2.11	0.40	0.49	0.45	1.08	1.98	2.65	2.17	2.64	0.03	0.25
43		-	0.51	2.92	0.11	0.23	0.10	1.03	2.87	1.22	3.67	4.26	0.75	0.97
85			-	0.76	0.36	0.28	1.17	0.25	2.61	3.48	3.06	3.50	2.61	1.20
91				-	1.80	1.68	3.34	0.55	5.47	10.2	10.2	10.6	7.33	5.67
19					-	0.09	0.94	0.75	2.58	3.57	3.08	3.59	0.71	0.89
39						-	0.23	0.84	0.66	3.76	3.27	3.78	0.87	1.03
87							-	1.72	1.68	2.29	1.75	2.27	0.68	0.37
26								-	3.37	4.82	4.37	4.88	1.96	2.00
17									-	0.01	0.57	0.06	2.91	2.46
21										-	0.85	0.09	4.62	3.71
88											-	0.78	3.96	3.06
40												-	4.70	3.74
36													-	0.44

XS 3

	8	43	85	91	19	39	87	26	17	21	88	40	36	42
4	0.94	0.73	0.57	0.48	0.04	0.14	1.01	0.23	1.93	0.42	0.13	1.41	2.77	1.50
8	-	0.75	1.32	1.29	0.93	1.11	0.09	1.15	1.10	0.51	0.63	0.14	2.45	1.69
43		-	1.70	1.66	0.70	1.13	0.84	1.24	1.86	0.03	0.26	0.82	4.94	2.08
85			-	0.14	0.65	0.54	1.36	0.42	2.84	0.87	0.49	1.63	2.60	1.33
91				-	0.56	0.42	1.34	0.30	2.87	0.82	0.44	1.61	2.92	1.42
19					-	0.20	1.00	0.29	1.94	0.40	0.11	1.07	2.93	1.55
39						-	1.17	0.12	2.45	0.58	0.23	1.33	3.26	1.57
87							-	1.21	0.04	0.60	0.70	0.25	2.42	1.70
26								-	2.52	0.64	0.29	1.39	3.09	1.51
17									-	0.96	1.09	0.38	5.22	2.55
21										-	0.19	0.49	2.41	1.51
88											-	0.67	4.88	2.11
40												-	3.29	1.94
36													-	0.27

Table 7.7a Dnorm values: spectral separation of heather canopies in airborne SPOT HRV data, May 1984. See table 7.6 for description of sites.

XS 1, XS 2

	8	43	85	91	19	39	87	26	17	21	88	40	36	42
4	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000
8	-	778	741	2000	232	415	446	1556	2000	1443	1998	1979	425	1450
43		-	1163	2000	590	984	1507	1126	2000	1993	2000	1999	1056	1588
85			-	2000	554	626	1124	996	2000	1811	0999	0999	1340	1989
91				-	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000
19					-	53	1041	891	2000	1874	1999	1998	640	1790
39						-	1927	2000	2000	1927	1999	1999	784	1883
87							-	1946	2000	1017	1992	1925	804	1369
26								-	2000	1999	2000	2000	1845	1999
17									-	1999	1454	1874	2000	2000
21										-	1569	977	1972	1999
88											-	444	1999	2000
40												-	1999	2000
36														676

XS 2, XS 3

	8	43	85	91	19	39	87	26	17	21	88	40	36	42
4	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000
8	-	1917	1947	2000	1517	1869	607	1983	2000	1955	1999	1999	1951	2000
43		-	1681	2000	808	1086	1981	1871	2000	1978	2000	1999	1999	1999
85			-	2000	477	334	1980	328	2000	1822	1999	1999	1990	2000
91				-	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000
19					-	107	1726	1056	2000	1807	1995	1998	1972	2000
39						-	1948	856	2000	1892	1999	1999	1983	2000
87							-	1957	2000	1416	1993	1919	1857	2000
26								-	1865	1997	2000	1999	1953	2000
17									-	1999	1884	1858	2000	2000
21										-	1560	790	1999	2000
88											-	625	2000	2000
40												-	1999	2000
36													-	1999

XS 1, XS 2, XS 3

	8	43	85	91	19	39	87	26	17	21	88	40	36	42
4	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000
8	-	1966	1982	2000	1727	1917	865	1985	2000	1973	1999	1999	1969	2000
43		-	1851	2000	1311	1603	1996	1909	2000	1999	2000	1999	1999	2000
85			-	2000	1063	871	1991	1021	2000	1911	1999	1918	1999	1999
91				-	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000
19					-	210	1865	1181	2000	1947	1999	1999	1998	2000
39						-	1974	1171	2000	1948	1999	1999	1996	2000
87							-	1998	2000	1485	1997	1953	1933	2000
26								-	2000	1999	2000	2000	1998	2000
17									-	1999	1896	1902	2000	2000
21										-	1758	994	1999	2000
88											-	919	2000	2000
40												-	2000	2000
36													-	1999

Table 7.7b TD values: spectral separation of heather canopies in airborne SPOT HRV data, May 1984

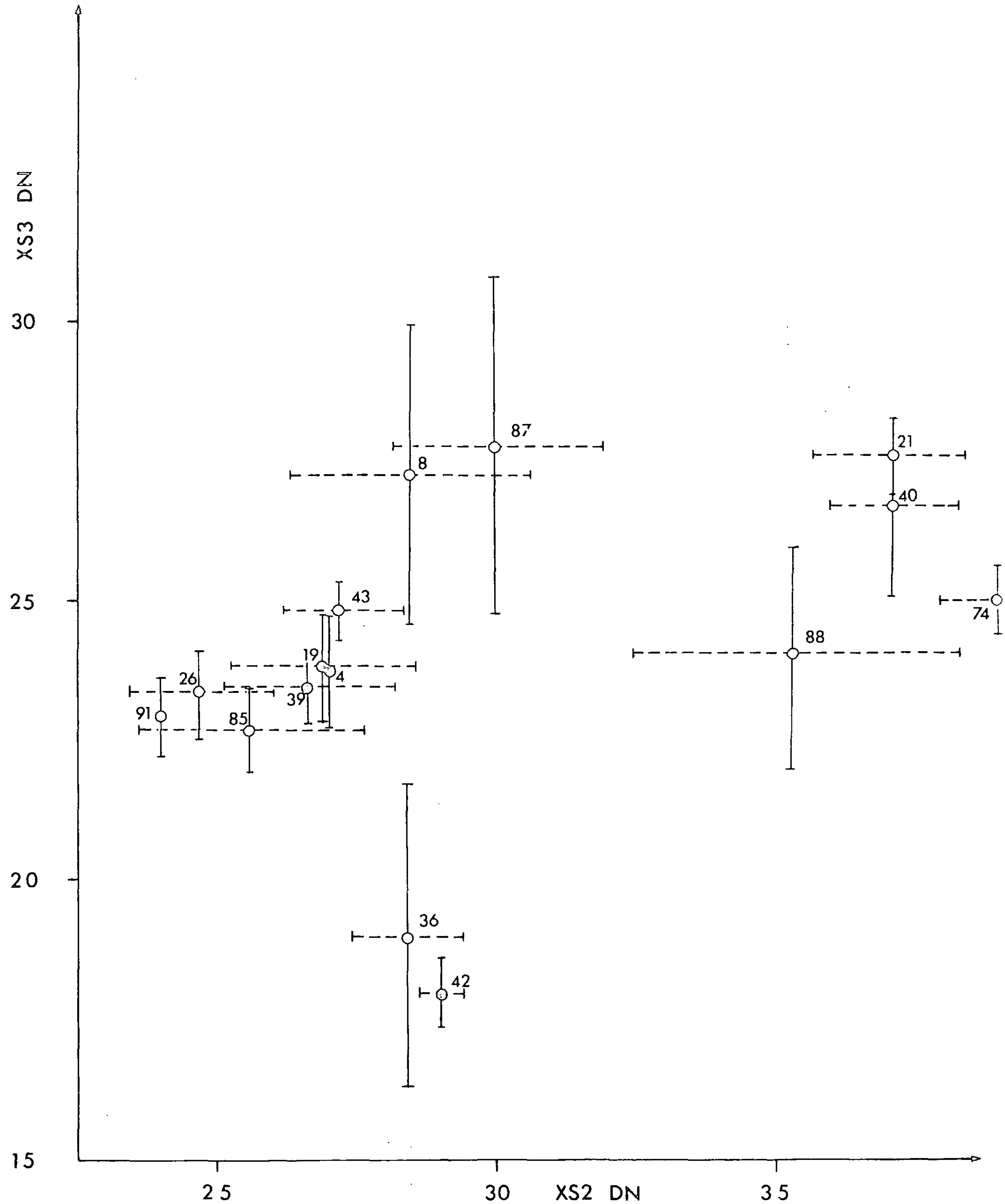


Figure 7.3 The spectral response of moorland test sites in the feature space defined by the airborne SPOT HRV bands May 1984

slightly higher differentiation between the mature/over-age heathers and the young heather canopies in the visible bands, particularly in XS1. Although this separation is not consistent this is clearly important in management terms.

Such a distinction was also implied in the May 1984 ATM data although in those data the increased separation came in the near-IR wavelengths and was mainly the result of greater uniformity within the over-age stands. In the May airborne SPOT HRV data the young heather stands have a very varied response although the internal variance of each site is similar to the July data. The variation in response means that the response of the young heather stands as a group overlaps considerably with that of the sites of partial cover (figure 7.3), which otherwise have a similar distribution to the July data.

The heather sites and the regenerating areas are however well separated in the visible bands of the July data. When used together (figure 7.4) the visible bands at the two dates allow a clear discrimination between the full canopies and the partially vegetated areas and some differentiation within the first group. The information available from this fuller sample suggests that temporal resolution may have greater importance in this environment than stated in chapter 6.

The near-IR band of the May data confirms the results of section 5.8 and makes the distinction between the new burn sites and all other sites much more clearly than the July data. The May data were acquired only two weeks after the end of the burning season in mid-April. The burning season had this year been extended by two weeks into April and these two weeks provided ideal burning conditions after a late spring (Brown, pers. comm.). The May data were therefore acquired at a time when the burnt surface had been virtually undisturbed. This suggests that the near-IR band will be useful in delimiting newly burnt sites if the data can be acquired at the right time.

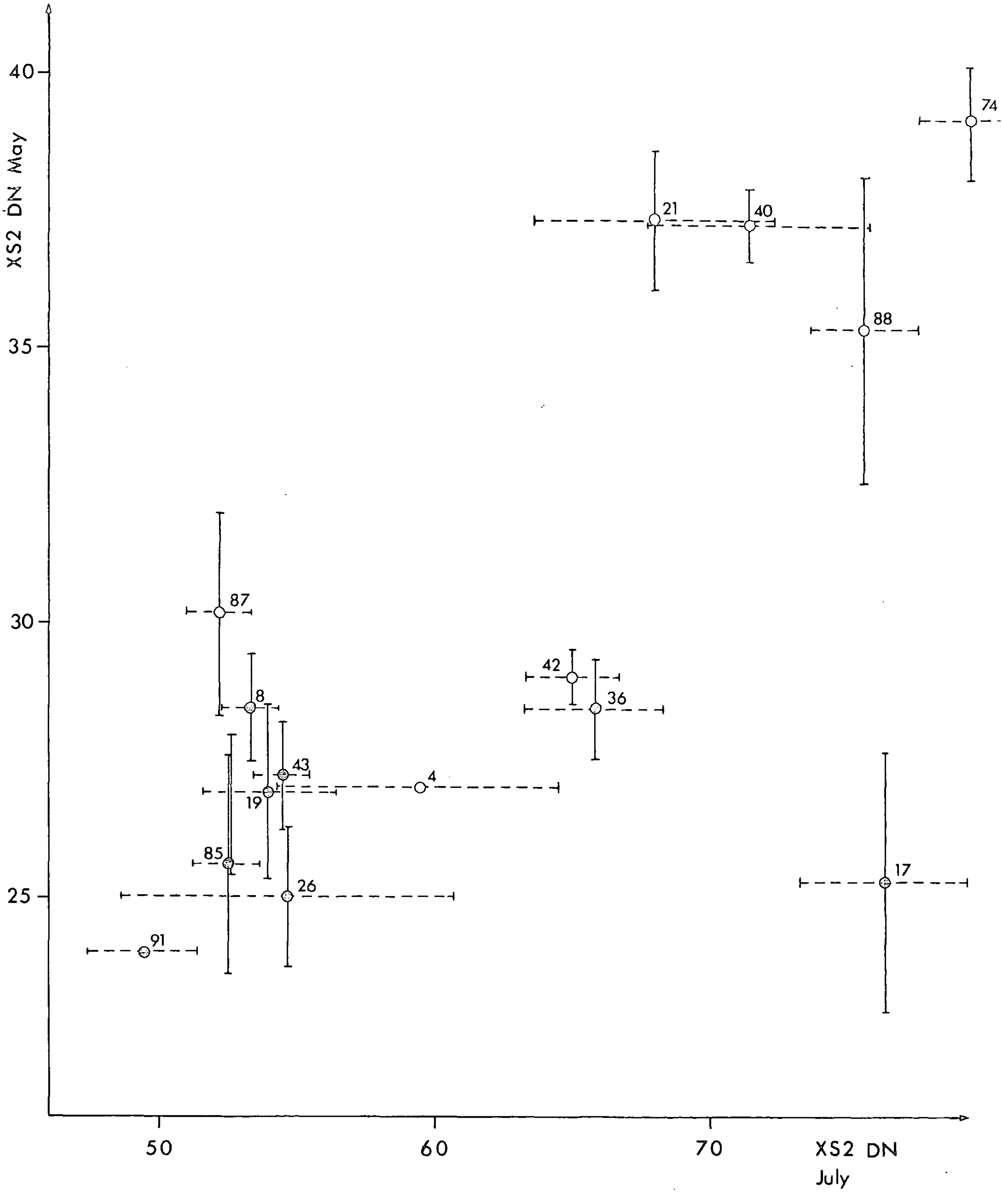


Figure 7.4 Increasing the spectral separation of the canopies by using airborne SPOT HRV data from both July and May flights.

There is however virtually no separation between the remaining partially vegetated sites and the established stands in this waveband (table 7.7). Individual samples of each class can be separated but there is no distinction between the classes as a whole. Apart from the isolation of the newly burnt sites the maximum levels of separation between the moorland classes are low in comparison with the July data and most of the discriminatory information is held in the visible bands (table 7.7).

7.4.2 Bracken

The airborne SPOT HRV data were examined briefly to assess their utility for mapping and monitoring bracken advancement onto the moor - identified in chapter 3 as a serious cause of degradation of the moorland resource. Bracken dominates about 12,140 acres of moorland in the North York Moors and is advancing at a rate of 1% a year. Section 3.4.2 in chapter 3 described the reasons for its nuisance value and the categories of stands to be identifed, and also noted that the National Park are collaborating with MAFF on an experimental clearance programme. Four of the sites in the experiment are covered by the airborne SPOT HRV data and their response is examined in both acquisitions. The aim is to determine whether the stands, of different degrees of vigour, biomass and uniformity of canopy, can be isolated from each other by their spectral response in the SPOT HRV wavebands.

The summary statistics of each site's spectral response and the accompanying separation statistics are given in table 7.8. Analysis concentrated on the July data as they were acquired close to the period of maximum biomass. They are expected to show the greatest sensitivity to differences in biomass and vigour between stands.

As expected, the two visible bands XS1 and XS2 are positively correlated ($r > .84$) at all the bracken sites. The response in XS2 at the Castleton west site is negatively correlated with XS3 ($r = -.78$) and this relationship is apparent from figure 7.5. There is no consistent

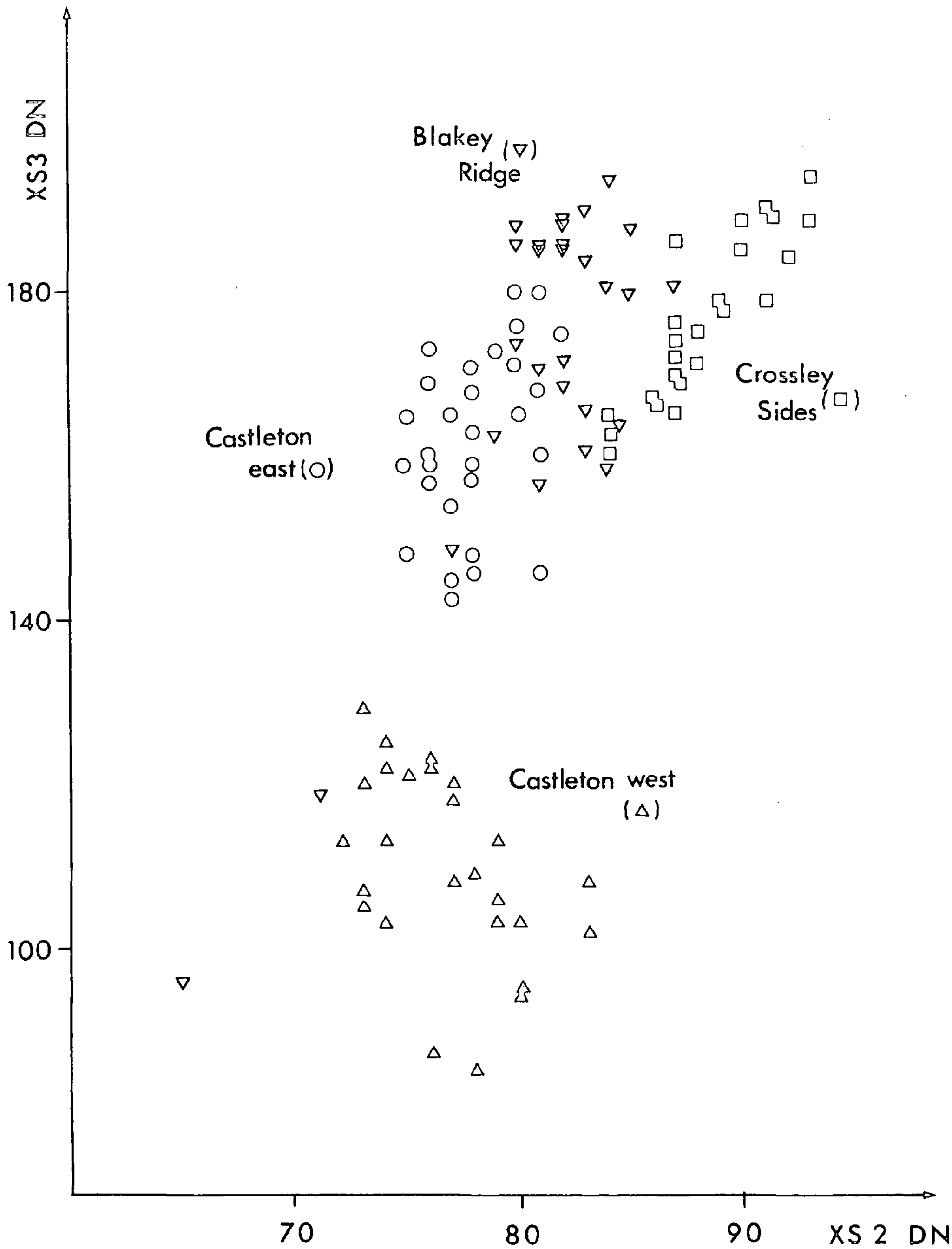


Figure 7.5 The separation of the bracken stands in the airborne SPOT HRV data, July 1984

Site		XS1	XS2	XS3
1 Blakey Ridge: sprayed in 1982, with 15	$\bar{x}$	78.13	69.84	152.56
	c.v.	5.904	6.507	15.800
2 Crossley Sides: actively invading heather		87.47	76.61	186.30
		3.613	3.641	10.485
3 Castleton Rigg west sprayed, irregular surface cover		77.29	73.09	119.34
		3.210	6.302	16.402
4 Castleton Rigg east more uniform cover, interspersed with *Calluna*		76.50	66.16	149.83
		5.443	6.016	12.364

Dnorm values

XS 1

	2	3	4
1	1.20	0.12	0.19
2		1.81	1.50
3			0.12

XS 2

	2	3	4
1	1.08	0.36	0.43
2		0.48	1.54
3			0.81

XS 3

	2	3	4
1	0.77	0.76	0.06
2		1.71	0.96
3			0.80

TD values

XS 1, XS 2

	2	3	4
1	1233	949	547
2		1971	1490
3			1706

XS 2, XS 3

	2	3	4
1	1071	991	235
2		1946	1552
3			1192

XS 1, XS 2, XS 3

	2	3	4
1	1337	1089	809
2		1989	1590
3			1795

Table 7.8 Spectral response of bracken sites in airborne SPOT HRV data, July 1984

relationship between visible and near-IR bands at the other sites. The visible bands make a clear distinction between the vigorous growth at the Crossley sides site and the established Castleton East stands. The irregular canopy of the Blakey Ridge site falls across these two sites and has greatest overlap with the Castleton East site, with which it has greatest ecological similarity. The variable response of the Castleton West site extends across all three sites in the visible bands but is isolated by its lower response in XS3. The within site variation in the IR bands is highest for the two cleared sites although there is no corresponding pattern in the visible bands.

The separation possible between the sites (table 7.8) is clearly insufficient to allow consistently accurate sub-division of the bracken belt if these stands are representative. It appears however that there is some potential for further investigation of a larger sample. In particular, recognition of the partly cleared sites depends on pattern or texture as well as on their averaged spectral information. A method of classification which takes this and the effect of topography into account would have greater success. This topic is discussed further by Weaver (1986), Birnie and Miller (1986) and Curran (1986b).

7.5 Change in distribution of variance with change in spatial resolution

This section uses the data described in section 7.4 and chapters 5 and 6 to examine the effect of changing spatial resolution on the spectral separation of moorland targets and therefore the relative importance of spectral and spatial resolution in this environment. As outlined in section 7.1 a decrease in spatial resolution is expected to alter the distribution of variance in the data, decreasing the proportion that is held within each class or site and thereby increasing the proportion that is held between classes. The effect of such a change is to increase the spectral separation of classes which have different mean responses. This section determines whether such a change occurs in the green, red and near-IR wavelengths of the data sets described in this thesis, where the integration area varies upwards from c. 1m x 1m.

Elements of a conventional analysis of variance (Silk, 1981) are used to compare the distribution of variance between the data sets. The change in variance within the spectrally variable classes, particularly the regenerating areas, is examined in detail. In further analysis (section 7.6) the maximum spectral separation available in the three bands of the reduced resolution airborne SPOT HRV data is compared to that available in analogous bands and the full 7 band feature space of the ATM data.

The results will identify which data set, and therefore spatial resolution, gives an optimal spectral separation of the common moorland canopies. When taken with the results of previous chapters this will define the relative importance of spatial, spectral and temporal resolution in monitoring the moorland environment. Chapter 8 concludes the thesis by discussing how data with different resolution characteristics should be selected to give the most useful information for each of the management tasks identified in this thesis.

Each observation in a data set can be expressed as the mean score or response for all observations plus two error terms, one which accounts for the fact that the observation falls into a class whose mean is located at a distance from the overall mean, and a second which accounts for its deviation from the mean of its class (figure 7.6). Analysis of variance (ANOVA) splits the total variation in a set of observations into these two components.

In the case of a single variable, here the response of each test site in a single waveband,

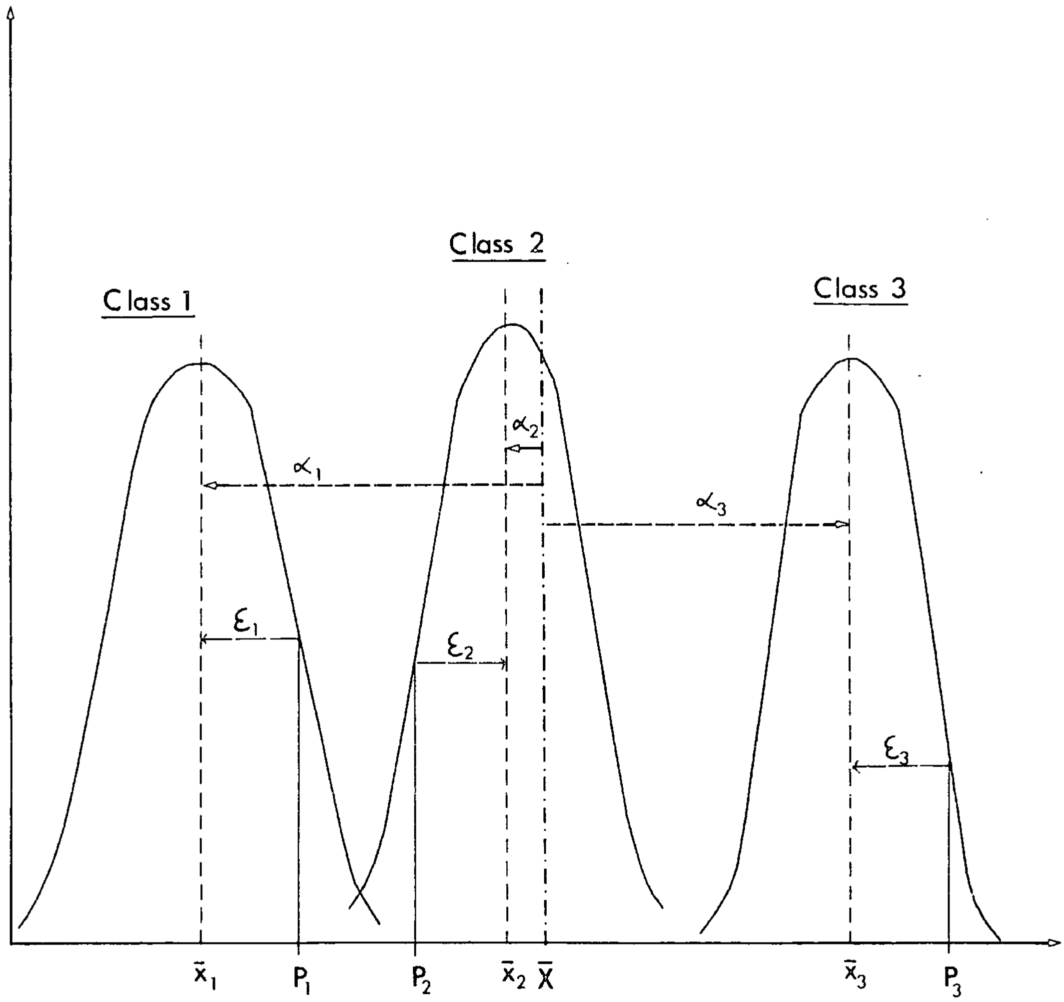
$$SS_T = SS_B + SS_W$$

where SS_T, the total variation or the total sum of squares, is the sum for all observations of their squared deviations from the overall mean.

SS_B, the between group sum of squares, is the sum of the squared deviations between each class mean and the grand mean, weighted by the size of the class. For these data this is the amount of variation in the data set which is caused by the differential response of the vegetation types in this waveband. SS_W, the within group sum of squares, is the sum of the squared deviations between individual observations and their class means and accounts for the natural variation in response which occurs within a class and is approximately normally distributed.

A conventional ANOVA seeks to refute the null hypothesis that there is no significant difference between the means of individual classes. If the means are similar then estimates of the overall variance derived from the two SS terms - will also be similar. The ratio of the two estimates can be compared to the percentage points of the F-distribution to determine whether an apparent difference between them is significant at a pre-determined level.

This step is however inappropriate for the purpose of this work. The degrees of freedom used to calculate the variance estimates depend on the number of classes and on the total number of observations in the data set. The number of test sites varies only slightly from one data set to another.



α_n: effect of class: distance of class mean from overall mean

ε_n: disturbance within class

Expression for P_n is therefore

$$P_n = \bar{X} + \bar{x}_n + \varepsilon_n$$

Figure 7.6 Description of terms used in Analysis of Variance (ANOVA)

Clearly the number of observations (pixels) at each site varies to a greater degree although a similar geographical area is covered at each site. The most useful summary statistic of the distribution of variance in this case is therefore the proportion of variance in each data set that is held within class. If the hypothesis that decreasing the spatial resolution also decreases the variation within each class is to be refuted, there will be no difference in the relative proportions of within and between class variation between data sets which have different spatial resolutions.

Table 7.9 summarises the SS_W term, expressed as a percentage of SS_T, for comparable sites and wavebands from the ground radiometer data, the 1984 ATM flights and the airborne SPOT HRV data. These calculations were not made for the 1983 ATM data and are inappropriate at the level of analysis used in the MSS data (section 7.3). As far as possible the same test sites were extracted from all data sets but some substitution proved inevitable

The overall distribution of variance is similar in corresponding bands of the two sets of ground radiometer data acquired in 1983. Most of the total variance in the visible bands is held between-class but, as expected from the data of chapter 4, the situation is reversed in the near-IR band.

The replacement of the Calluna/Eriophorum mix with the new burn site in 1984 causes a dramatic reduction in the amount of within-class variance in the near-IR. The visible bands are also affected and the proportion of variance held within class in the green band of the 1984 data is consistently lower that that in the 1983 data. The amount of within-class variation in the red band of the August data however does not follow this pattern and is unexpectedly high. This reflects the increased and variable response in the heather class, as described in chapter 4. The differences between the sets of ground radiometer measurements are expected as only one example of each canopy was measured and the number of sample points in each canopy is small. Individual sample points can therefore have a strong

	Green	Red	Near-IR
Ground radiometer data			
July 1983	25.74	17.19	56.98
August 1983	20.40	10.32	65.92
May 1984	13.87	9.23	18.22
August 1984	15.80	20.93	28.72
ATM data			
May 1984 extended sample	14.88	19.24	32.43
August 1984			
basic sample	4.04	21.69	21.59
extended sample	7.26	26.85	20.77
Airborne SPOT HRV data			
May 1984			
basic sample	11.49	13.95	24.49
extended sample	15.43	16.95	54.22
July 1984			
basic sample	5.2	5.19	27.16
extended sample	11.51	10.30	31.89

Table 7.9 The proportion of variance held within class in the ground radiometer and airborne sensor data sets.

influence on the overall distribution of variance. These data show however that a maximum of about 20% of the variance in the visible bands and 20-30% of that in the near-IR band can be expected to be held within class for these sites at this fine spatial resolution.

The hypothesis can be tested more rigorously in the ATM data and the airborne SPOT HRV data where a more representative sample of cover types is available. Compared to the ground radiometer data all the sets of airborne data are expected to have a lower proportion of their total variance held within-class.

Two sets of calculations were made for each of the aircraft data sets. The first set uses single test sites of each cover type which are an exact or a close match to those used in the ground radiometer experiments. It was not possible to make this calculation for the May 1984 ATM data because of the limited number of test sites, as described in chapter 6. In the second set of calculations each cover type is represented by a number of sample sites. These data are expected to have a higher within-class variance than the first set of calculations, because of the differences in response between samples of similar canopies as shown in figure 7.4. They are however a more accurate picture of the variability in spectral response in each class over the moor. The results are summarised in table 7.9.

In the basic set of calculations for the August 1984 ATM data the proportion of the total variance held within-class in the green waveband is very low, at 4.04%. The results in the red and the near-IR bands (21.69% and 21.59% respectively) are a closer match to those of the August 1984 ground radiometer data. This pattern is maintained in the extended data set. Compared to the basic set the proportion of variance held within-class rises slightly in both the visible bands, but the difference between them is maintained. The distribution in the near-IR bands is more stable and the proportion of variance held within-class, at 20.77%, falls below that in the red band.

In the May data, where the limited choice forced a rather different selection of sites, the pattern is closer to the general one of the ground radiometer data. The proportion of variance held within-class in the two visible bands is lower than that in the near-IR band (14.88% and 19.25% vs. 32.43%). In absolute terms the amount of variance within-class in the red and the near-IR bands of the May data is appreciably higher than that in the ground radiometer data of the same date although the levels are similar to those in the August ground radiometer data.

In summary, the only dramatic difference in the overall distribution of variance between the ground radiometer and the airborne TM data is in the considerable reduction of within-class variance in the green band. The results in the red band of the ATM data are consistent at c. 20% across all acquisitions and are similar to or slightly higher than those in the ground radiometer data. Given the difference in the number and diversity of the test sites between the data sets, the distribution of variance in the near-IR is remarkably constant.

As noted in chapter 5 (section 5.4.2) the variation in response at each site is considerably and consistently higher in the red band of the ATM data than it is in the green band. This difference between bands, although present, is much less marked in the ground radiometer data. The results, in table 7.9, imply that the green band is affected more strongly by changing spatial resolution than is the red band. The uncertainties associated with the data mean however that this can be only a tentative conclusion.

In contrast to the ATM data, a similar amount of variance is held within-class in both the green and the red bands of the basic data set extracted from the airborne SPOT HRV data. In the July data this is low (5.2% and 5.19%) and approximates the result in the green band of the corresponding ATM data (4.04%). The results in the May data are higher at 11.49% and 13.95% respectively but are still far from the high proportion accounted for in the red band of the extended ATM data (26.85%). The closer match between the two visible bands is expected from the discussion in section 7.4, as the test sites show a similar distribution of variance and separability in both wavebands. The distribution of variance in the near-IR in both the May and the July basic data sets remains similar to that in the ATM data, but, as expected from section 7.4, it is high in the extended airborne SPOT HRV data at both dates.

In the extended extracts from the airborne SPOT HRV data sets, a rise in the amount of within-class variance in the July data means that the results from the two dates are similar. In the green band they are similar to or slightly higher than those in the ATM data; the spread is greater in the red band although the amount of within class variance is lower in both the airborne SPOT HRV data sets. The proportion of within class variance is considerably higher in the airborne SPOT HRV data than in the ATM data.

These results are not however a substantial improvement on those from the ground radiometer data collected at a similar time. The visible band of the basic SPOT July data do show a considerable reduction in the amount of variance held within class. In all other respects however the distribution of variance in the data from the two sensors is very similar.

The amount of variance held within class is summarised graphically in figure 7.7. It is clear that when all the data sets are considered together, and even when the variable 1983 ground radiometer data are excluded, there is no clear evidence for a marked and consistent reduction in within-class variance with decreasing spatial resolution.

These results imply that for the cover types examined here and in data with these spatial resolutions, spatial resolution has little effect on the overall distribution of variance between and within these classes.

The data were examined in more detail to determine whether, within this result, some classes were being differentially affected by the change in spatial resolution. The proportion of the total within-class variance that is accounted for by different sites and classes in each data set is listed

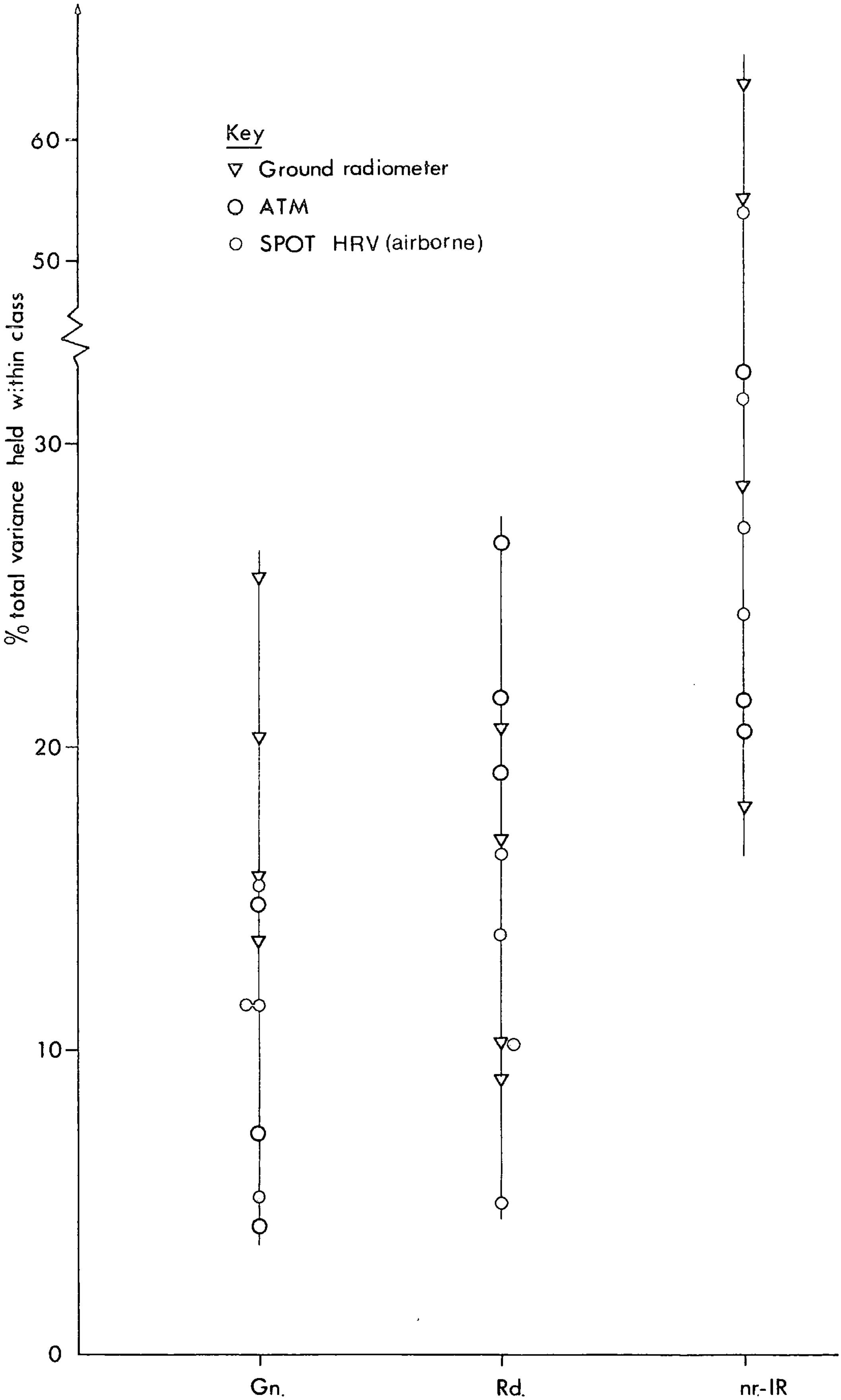


Figure 7.7 Summary graph: proportion of variance in each data set held within class

	Partly exposed sites			Heather/sedges mix		
Ground radiometer						
July 1983	11.92	25.66	51.75	46.05	27.06	22.71
August 1983	13.95	27.30	48.31	58.68	39.58	32.61
May 1984	71.81	66.44	41.46	n/a		
August 1984	21.29	10.14	81.21	n/a		
ATM data						
May 1984						
extended	53.27	46.44	37.59	45.96	39.69	34.64
August 1984						
basic	31.82	21.59	43.25	12.35	17.20	10.08
extended	31.38	25.46	38.52	9.07	14.09	8.48
Airborne SPOT HRV data						
May 1984						
basic	69.73	74.64	46.25	6.77	9.29	4.83
extended	28.12	21.22	39.52	2.01	6.35	4.83
July 1984						
basic	16.54	26.22	35.92	18.56	16.54	22.07
extended	31.37	37.24	34.52	7.68	12.10	16.30

Table 7.10 The proportion of within class variance in selected data sets which is accounted for by specific test sites

in table 7.10. If altering the spatial resolution of the data has no effect on the spectral response of any target then the different elements of the moorland community will account for more or less constant amounts of the total within-class variance in all data sets. However the spectrally variable classes, in particular the regenerating surfaces and the Calluna/Eriophorum mix may become more uniform with decreasing spatial resolution, in which case they will account for a progressively reduced proportion of the total within class variance. This effect may be masked in an analysis of the overall distribution of variance which also depends on the absolute response of the training sets. It will however have considerable implications for the separation and classification of these sites.

The figures for the ground radiometer data quantify the results shown in the graphs of chapter 4. The fully exposed peat and heather stands have a relatively uniform response. The regenerating peat surface and, where measured, the mixed heather/sedges site provides the major amount of within-class variance in these data sets.

The distribution of the total within-class variance between the test canopies is very similar in the July and the August 1983 ground radiometer data. In the green waveband the mature heather stand accounts for a very small proportion of the total (5.69% and 5.29% respectively), the regenerating peat surface accounts for slightly more (11.92% and 13.95%), and the heather/sedge mix accounts for the largest element (46.05% and 58.68%). In the red waveband the heather canopy also has a low proportion of the total variance. The share of the regenerating peat surface and the mixed heather/sedges are closer however, at 25.66% and 27.06% in the July data, and 27.30% and 39.58% in the August data. In the near-IR band the regenerating peat surface becomes the main source of within-class variance.

These results are roughly paralleled in the May 1984 ground radiometer data. In the absence of the mixed heather/sedges site the regenerating surface is the main source of within-class variance in all bands. This is particularly high in the visible bands at 71.81% in the green band and 66.44% in the red. Compared to the 1983 data the variance in this class is reduced in the near-IR, which keeps the proportion of variance it accounts for in this band at a similar level to the 1983 data.

The dominance of the mixed heather/sedges site is weakened considerably in the ATM data. In the basic August data set the mixed stand has a variance rather less than that of the mature heather stand in both the green and the red bands (12.35% vs 16.54% and 17.20% vs 26.89% respectively). The distribution of variance in the near-IR band is similar to that in the ground radiometer data, but also with some reduction in the importance of the mixed site. The regenerating peat surface is therefore the main source of variance in all bands in this data set although only in the green band has it increased its share of the total variance.

This pattern of a more equable distribution of variance persists in the extended analysis of the August data. This suggests that the response of the different elements of the mixed site are being averaged into a composite signature in the manner described in section 4. . In the more limited set of sites available in the May data however, the regenerating and the mixed sites have approximately equal importance in these wavebands.

Compared to the ATM data the regenerating surface and the mixed site account for slightly more equal amounts of the total variance in the basic data set extracted from the July 1984 airborne SPOT HRV data. This is most apparent in the green and the near-IR bands. When the analysis is extended to the fuller data set the amount of variance accounted for by the mixed site falls slightly and is below that within the full heather canopy. This has the effect of bringing the distribution of variance in all bands to a similar pattern to that in the corresponding data set of the ATM data.

In the basic May airborne SPOT HRV data the regenerating site dominates the distribution of variance across the classes, accounting for 69.73%, 74.64% and 81.41% of the total in the green, red and near-IR bands respectively. This dominance is however considerably reduced in the extended data set, where the figures are close to those in the July data. The results of this analysis are summarised graphically in figure 7.8. They show, for these test sites, that although there is change between the data sets in the way in which the within-class variance is distributed, it is not consistently linked to change in spatial resolution. The variance in the mixed heather/sedges class is high in the ground radiometry data and generally lower in the airborne data but there is no clear division between the two. At least some of the fluctuations in all classes will be due to substitution between test sites.

As in the overall distribution of variance between and within class there is a consistent dichotomy in the distribution of within-class variance between the visible and the near-IR bands. The distribution in the near-IR band shows only minor changes between data sets which have different spatial resolutions. The regenerating sites accounts for between 35% and 52% of the variation in all cases although the amount accounted for by the mixed site is more variable. The visible bands are, as noted in chapter 4, sensitive to the differences between canopy types. The distribution of the within-class variance in the visible band shows more marked changes from one data set to another and between the basic and the extended data sets.

Taken together, the results of this chapter show that whilst spatial resolution is of critical importance in deciding at what spatial scale targets can be recognised, it has little clear impact on the distribution of variance amongst the test sites. The largest pixel size examined here (16m x 8m) is close to that of the SPOT HRV sensors but is still considerably below that of the TM. It does however match or exceed any clear spatial periodicity of variation within the individual patches of the moorland landscape. The data sets therefore span the critical thresholds of variation within the patch. No further change in the distribution of variance is expected until the spatial resolution is decreased to the point where the individual patches cannot be located.

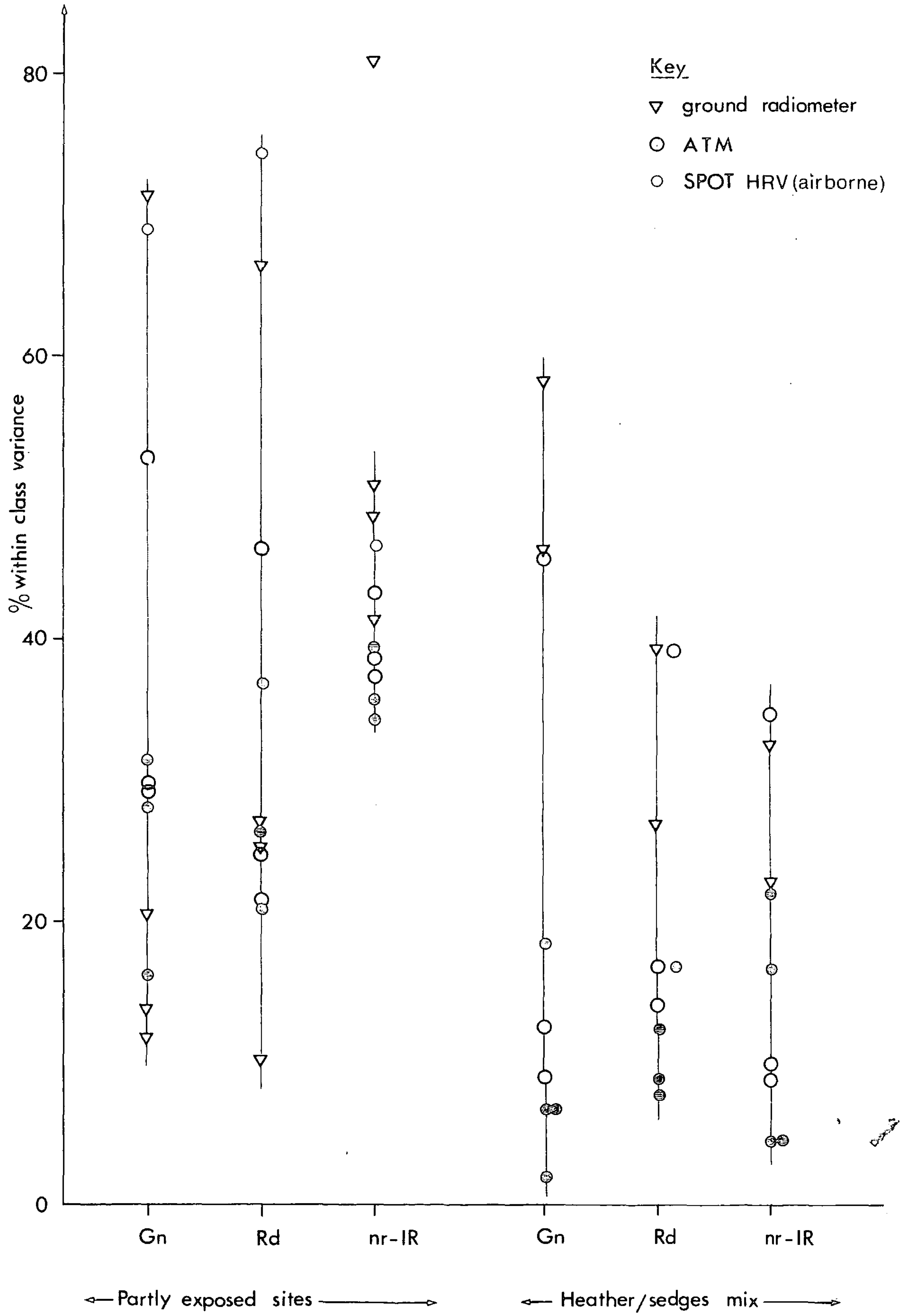


Figure 7.8 Summary graph: proportion of variance accounted for by test sites in data sets with different spatial resolutions

7.6 Maximum levels of spectral separation in the ATM and the airborne SPOT HRV data sets.

The level of separation of these test sites in the green, red and near-IR wavebands was examined briefly in the ATM data and the airborne SPOT HRV data to examine the implications of these results for the spectral separation of targets. The TD values for comparable test sites in the August 1984 ATM data and the July airborne SPOT HRV data are summarised in table 7.11. They show that the maximum degree of spectral separation between these sites is similar in both data sets. The regenerating sites noted here are rather more clearly separated from the young heather stands in the airborne SPOT HRV data. A different selection of sites however gives values close to those from the ATM data.

The mixed heather/sedges site is consistently confused with both the mature and the young heather canopies in this reduced feature space. The signature of this site, when the variation due to its different components is averaged out, is not therefore sufficiently different to that of the surrounding stands for it to be clearly identifiable. These sites are however discriminated more clearly in the ATM data when the thermal or the mid-IR bands are included in the analysis.

As noted throughout chapters 5 and 6 the thermal and the mid-IR wavebands contain similar descriptive and discriminatory information to the visible bands for a number of sites. The omission of the longer wavelengths is therefore not critical in these cases. However, in the isolation of the regenerating peat surface, the bracken stand and some of the elements of the heather class, the mid- and the thermal IR bands carry unique and valuable discriminatory information. The results of this chapter have shown that decreasing the spatial resolution of the data has little effect on the spectral separability of the most variable of these sites in the visible and near-IR bands. Given sufficient spatial resolution for their location, the availability of the correct spectral information is clearly

XS 1, XS 2, XS 3: May 1984 airborne SPOT data

	over-age/mature				mature/building				regenerating				new burn	
	8	43	85	91	19	39	87	26	17	21	88	40	36	42
4	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000
8	-	1966	1982	2000	1727	1917	865	1985	2000	1973	1999	1999	1969	2000
43		-	1851	2000	1311	1603	1996	1909	2000	1999	2000	1999	1999	2000
85			-	2000	1063	871	1991	1021	2000	1911	1999	1918	1999	1999
91				-	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000
19					-	210	1865	1181	2000	1947	1999	1999	1998	2000
39						-	1974	1171	2000	1948	1999	1999	1996	2000
87							-	1998	2000	1485	1997	1953	1933	2000
26								-	2000	1999	2000	2000	1998	2000
17									-	1999	1896	1902	2000	2000
21										-	1758	994	1999	2000
88											-	919	2000	2000
40												-	2000	2000
36													-	1999

TM 2, TM 3, TM 4 ATM

	over-age			young heather			regenerating			new burn
	17	18	21	10	12	9	5	6	7	23
14	1553	1642	1075	1695	1901	1751	2000	2000	2000	2000
17	-	1513	1057	1952	1999	1958	1999	1999	2000	2000
18		-	1183	1470	1892	1769	1999	1999	1999	2000
21			-	1621	1904	1518	1999	1999	1999	1993
10				-	1014	955	2000	1927	1956	1881
12					-	1196	1936	1956	1839	1858
9						-	1803	1915	1937	1998
5							-	221	1137	1902
6								-	1064	1945
7									-	1999

Table 7.11 Maximum spectral separation of test sites in comparable wavebands of the airborne scanner data sets. Site numbers for top and bottom matrices refer to descriptions in tables 6.2 and 7.4 respectively.

the limiting factor in their delimitation.

7.7 Summary and conclusion

The two hypotheses tested in this chapter are, firstly, that the quality of spectral information in an image is irrelevant without a suitable spatial resolution, and secondly that a decrease in spatial resolution causes a decrease in the variation of spectral response at each site.

The first hypothesis, examined particularly in section 7.3, has not been refuted. The limitation on the use of the Landsat MSS data in routine moorland management is that the pixel size is too large to either locate the boundaries of the major communities with reasonable accuracy or identify the elements of the heather patchwork. The relatively coarse resolution of the sensor is however an advantage at the small-scale reconnaissance level, as it precludes confusion between elements of the heather mosaic and the major communities outside the moorland core. Clearly the requirements for a spatial resolution which will allow accurate location of the target as well as a uniform spectral response within it will tend to work against each other. With the use of standard median filters and edge detection algorithms however, the MSS data will come close to the optimal data set for mapping the major commuities in the North York Moors.

The second hypothesis, which implies that decreasing the spatial resolution will increase the spectral separation of the targets, is refuted for the test sites and data used in this chapter. The variation inherent to airborne sensor data means that a more rigorous test, preferably by systematically degrading a basic high resolution data set, is needed to identify the thresholds of spatial resolution which are important in this environment.

The results show however that a similar degree of spectral separation of moorland targets can be expected in the visible and the near-IR bands of fine resolution airborne scanner data, Landsat TM or SPOT HRV data. In this sense using a sensor with a low spatial resolution is an effective method of data reduction because it retains the required spectral separation whilst discarding extraneous spatial information and reducing the volume of data to be dealt with. It does not improve the spectral separation of the targets, changing the spatial resolution cannot therefore compensate for the removal of pertinent spectral information.

Chapter 8 extends this discussion and, by examining the conclusions of each of the previous chapters, defines how data from the Landsat MSS, TM and the SPOT HRV sensors might best be brought together into a GIS for moorland management.

Chapter Eight: The use of multispectral remote sensing in the management of the North York Moors

8.1 Introduction

This chapter summarises the results of the thesis and examines their implications for the use of multispectral remote sensing in the management of the North York Moors. As noted in previous chapters the integration of remotely sensed data with more conventional map or ground surveys in a GIS is a desirable long term goal. In practice such a system is unlikely to be available in the near future, the discussion in this chapter therefore concentrates on the way in which remote sensing, and particularly data from current earth resources satellites, can be used to immediate effect in the management of the moorland environment.

8.2 Summary of results

Chapter 2 outlines the degree to which airborne scanner data can be used to predict results from satellite sensors, concluding that they can give useful estimates in the absence of satellite sensor data but in their raw state are a poor simulation. Further technical discussions of the Landsat MSS, TM and SPOT HRV systems in chapter 2 suggests that vegetated targets will be isolated and recognised most reliably in data from the Landsat TM. Analysis of a number of sets of ground radiometer data in chapter 4 confirms the suggestion of chapter 3, that at least some of the elements of the moorland habitat can be isolated and recognised by their spectral response. This analysis also demonstrates how, even in a simple data set, the parameters of spectral, spatial and temporal resolution interact to affect the probability of error in classifying a sample point.

The importance of spectral resolution is examined further in the analysis of airborne TM data in chapter 5, in which the problems of using measures of statistical separation as surrogates for classification accuracy are also discussed. The results show that none of the seven ATM bands examined can isolate all components of the moorland community but that, in most cases, the different cover types are separable if a particular combination of spectral information is available. In a number of cases the presence of one particular waveband is critical. The wavebands which, in combination, give the best separations are not necessarily independent sources of spectral information, and classes which show high inter-band correlations in their spectral response are as clearly separated from the remaining samples as those which show very little inter-band correlation. This means that the optimum set of wavebands cannot be deduced simply from the dimensionality of the data. The practical implications of these results are firstly that a number of different waveband combinations may be needed to isolate one class in the moorland community from all others, and secondly that relatively minor changes in the amount and type of spectral information used can have a considerable impact on the probability of error in classification.

Chapter 6 examines the effect of seasonal and episodic change in the moorland on the spectral response of its constituents, and therefore on the amount and type of spectral information needed to isolate them. The analysis shows that the identity of the waveband combinations which give the best separations between cover types do change over time, as do the levels of separation attained. The isolation of the sedges and the bracken from all other stands is affected most strongly but only minor changes occur within the heather-dominated areas. Newly burnt areas can be identified in the near-IR band of data acquired close to the date of the burn. It appears however that relatively minor variations in antecedent environmental conditions can have a disproportionately strong effect on the amount and type of discriminating information in the data set, although some of the discrepancies found can be attributed to uncorrected systematic error in the airborne data. At the level of mapping and managing the gross vegetational structure of the moors therefore, temporal resolution is an important characteristic of multispectral remotely sensed data. Where the aim is to map the distribution of the age classes of heather it is secondary to spectral resolution.

Chapter 7 examines the effect of changing spatial resolution on the spatial definition and spectral separation of the moorland targets. The spatial resolution of the Landsat MSS is simultaneously a limitation and an advantage on its use in moorland management. It precludes precise location of vegetation boundaries but returns an integrated, uniform response from the moorland patchwork which allows the moor as a whole to be separated from the other major communities.

Further analysis of the airborne and ground radiometer data sets shows that there is no appreciable change in the spectral discrimination of moorland targets (in the common visible and near-IR bands) with change in spatial resolution. Remotely sensed data will therefore continue to return useful information on the moorland mosaic if the spatial resolution allows neighbouring patches to be delimited from each other.

In summary, analysis of the airborne scanner data has shown that spectral resolution is an important characteristic of remotely sensed data at all levels of management. Temporal resolution is important for mapping the gross vegetational structure of the moor. Within the moorland area, spatial resolution has little effect on the spectral separation of targets but determines the size of vegetation patch which can be located and identified. At a less detailed scale, where the aim is to locate the major communities of agriculture (split to pasture and arable), bracken and heather moor, the interdependence of the 3 resolution parameters is more apparent. In particular, examination of the Landsat MSS data showed that the need for spatial precision in the location of targets must be balanced against the requirement to suppress spectral variation within the moor.

8.3 Implications for use of satellite sensor data

If extrapolated to satellite sensors (and given the problems of such extrapolation outlined in chapter 2) the results summarised above suggest that none of the Landsat MSS, TM or SPOT HRV sensors will, individually, produce data which will meet the requirements of all the management problems discussed in chapter 3. As described in chapter 7, Landsat MSS data will provide information at the reconnaissance level. Both Landsat TM and SPOT HRV data will provide information on the age distribution of heather within the moorland patchwork, where the mapping units are newly burnt surfaces, regenerating surfaces and established stands. Mapping the locations of new burns year by year is a simple way of monitoring the level of management on the moors and thereby pre-empting the consequences of catastrophic fire in over-aged heather stands. A map of the three categories of cover, drawn up at less frequent intervals, would provide an estimate of the area of productive moorland and identify areas where vegetation is slow to re-establish after controlled or accidental burning. Further work with Landsat TM and SPOT HRV data is needed to establish firstly whether the age distribution of the heather can be broken down further in these data, and secondly the level of discrimination that is possible between bracken stands at different stages of development.

As noted in section 8.1 above a fully-fledged GIS, integrating remotely sensed data with other spatially referenced data sets such as substrate type, estate boundaries and stocking densities is a desirable long-term goal. In the meantime, the conceptual framework of GIS (see Smith et al., 1987) is a suitable framework for determining the way in which remotely sensed data should be selected and integrated with existing management information.

The hypothesis under-lying this thesis is that multi-spectral remotely sensed data can provide sufficient critical information on the distribution and status of moorland vegetation to make their use an important part of management. This hypothesis has not been refuted for the data examined and the technique is under further investigation by the North York Moors National Park Authority.

References

Aase, J. K. and Siddoway, F. H., 1981, Assessing winter wheat dry matter production using spectral reflectance measurements. Remote Sensing of Environment, 11, 267-277.

Acevedo, W., Buis, J. and Alexander, D., 1984, Changes in classification accuracy due to varying Thematic Mapper and Multispectral Scanner spatial, spectral and radiometric resolution. 18th International Symposium on Remote Sensing of Environment, (University of Michigan, Ann Arbor), 3 (abs.)

Ajai, M.N., Gopalan, A.K.S. and Kamat, D.S., 1985, Discrimination of winter crops using temporal-spectral profiles. International Journal of Remote Sensing, 6, 1575-1580.

Allaby, M, 1983, The Changing Uplands. (Countryside Commission, Cheltenham).

Amis, M. L., Lennington, R. K., Martin, M. V., McGuire, W. G. and Shen, S. S., 1981, Evaluation of USDA large area crop estimation techniques. 7th International Symposium on Machine Processing of Remotely Sensed Data, (Purdue University, Lafayette), 26-33.

Anderson, W. H., Wentz, W. A. and Treadwell, B. D., 1980, A guide to remote sensing information for wildlife biologists. In Schemnitz, S. D. ed., Wildlife Techniques Manual, 4th edition, (The Wildlife Society, Washington D.C.), 291-303.

Anuta, P. E., Bartolucci, L. A., Dean, M. E., Lozano, D. F., Malaret, E., McGillem, C. D., Valdes, J. A. and Valenzuela, C. R., 1984, Landsat-4 MSS and Thematic Mapper data quality and information analysis. IEEE Transactions on Geoscience and Remote Sensing, GE-22, 222-236.

Badhwar, G.D., 1984, Use of Landsat derived profile features for spring small grains classification. International Journal of Remote Sensing, 5, 783-797.

Badhwar, G.D. and Henderson, K. E., 1982, A comparative study of the Thematic Mapper and Landsat spectral bands from field measurement. 8th International Symposium on Machine Processing of Remotely Sensed Data. (Purdue University, Lafayette), 266-272.

Baker, J. R., 1981, The Norfolk Broads: monitoring changes in vegetation cover using Landsat data. In Matching Remote Sensing Technologies and Their Applications, (Remote Sensing Society, Reading), 123 (abstract only).

Barclay-Estrup, P., 1969, Description and interpretation of cyclical processes in a heath community. I. Vegetational change in relation to the Calluna cycle. Journal of Ecology, 57, 737-758.

Barclay-Estrup, P., 1970, Description and interpretation of cyclical processes in a heathland community. II. Changes in biomass and shoot production during the Calluna cycle. Journal of Ecology, 58, 243-249.

Barclay-Estrup, P., 1971, Description and interpretation of cyclical processes in a heathland community. III. Microclimate in relation to the Calluna cycle. Journal of Ecology, 59, 143-166.

Barnsley, M. J., 1984, Effects of off-nadir view angles on the detected spectral response of vegetation canopies. International Journal of Remote Sensing, 5, 715-728.

Barnsley, M. J., 1986, Derivation of a globally-applicable index of off-nadir effects. Proceedings of NERC 1985 Airborne Campaign Workshop, ITE Monkswood, Abbots Ripton, November 1986, (NERC, Cambridge), E-1 - E-10.

Baudoin, A., 1986, Preliminary results from SPOT-1. International Archives of Photogrammetry and Remote Sensing 26, 1, (abstract only).

Begni, G., 1982, Selection of the Optimum Spectral Bands for the SPOT Satellite. Photogrammetric Engineering and Remote Sensing, 48, 1613-1620.

Bernstein, R., Lotspeich, J. B., Myers, H.J., Kolsky, H. G. and Lees, R.D., 1984, Analysis and processing of Landsat-4 sensor data using advanced image processing techniques and technologies. IEEE Transactions on Geoscience and Remote Sensing, GE-22, 192-221.

Betts, A.J.A., 1984, An investigation into the spectral properties of upland forestry using Landsat MSS data. Unpublished M.Sc thesis, University of London.

Birnie, R.V. and Miller, D.M., 1986, The bracken problem in Scotland, a new assessment using remotely sensed data. In Smith, R.T. and Taylor, J., eds, Bracken: Ecology, Land Use and Control Technology, (Parthenon, Carnforth), 43-55.

Birnie, R. V., and Williams, J. M., 1985, Monitoring iceberg production using Landsat data. Proc. Univ Dundee Summer School (Remote Sensing Applications in Civil Engineering) Dundee Sept. 1984, ESA SP-216 1985, 165-167.

Blanchard, L. E. and Weinstein, O., 1980, Design Challenges of the Thematic Mapper. IEEE Transactions on Geoscience and Remote Sensing, GE-18, 146-160.

Budd, J., 1985, The potential of SPOT satellite imagery for habitat monitoring. Final report to National Remote Sensing Centre, on research conducted as part of the 1984 SPOT simulation campaign.

Buis, J. S., Acevedo, W., Wrigley, R. C. and Alexander, D. A., 1983, The role of spatial, spectral and radiometric resolution on information content. 9th International Symposium on Machine Processing of Remotely Sensed Data, (Purdue University, Lafayette), 330-336.

Carneggie, D. M., Schrumpf, B.J., and Mouat, D. A., 1983, Rangeland Applications. In Colwell, R. N. ed., 1983, Manual of Remote Sensing, 2nd edition, (American Society for Photogrammetry and Remote Sensing, Falls Church), 2325-2384.

Chevrel, M., Courtois, M. and Weill, G., 1981, The SPOT Satellite Remote Sensing Mission. Photogrammetric Engineering and Remote Sensing, 47, 1163-1171.

Colvocoresses, A. P., 1977, Proposed parameters for an operational Landsat Photogrammetric Engineering and Remote Sensing, 43, 1139-1145.

Colovocoresses, A. P., 1979, Multispectral Linear Arrays as an alternative to Landsat-D. Photogrammetric Engineering and Remote Sensing, 45, 67-69.

Colwell, J. E., 1974a, Grass canopy bidirectional spectral reflectance. 9th International Symposium on Remote Sensing of Environment, (University of Michigan, Ann Arbor), 1061-1085.

Colwell, J. E., 1974b, Vegetation canopy reflectance. Remote Sensing of Environment, 3, 175-183.

Colwell, R. N., 1956, Determining the prevalence of certain cereal crop diseases by means of aerial photography. Hilgardia, 26, 223-286

Coppins, B. J. and Shimwell, D. W., 1977, Cryptogram complement and biomass in dry Calluna heath of different ages. Oikos, 22, 204-209.

Council for National Parks, 1985, Information Pack: Know your National Parks. (CNP, London)

Crist, E. P., 1984, A spectral haze diagnostic feature for normalising Landsat Thematic Mapper data. 18th International Symposium on Remote Sensing of Environment, Paris 1984 (author's preprint).

Crist, E. P. and Cicone, R. C., 1984, A physically based transform of Thematic Mapper data - the TM tasseled cap. IEEE Transactions on Geoscience and Remote Sensing, GE-22, 256-263.

Crist, E. P. and Kauth, R. J., 1986, The tasseled cap de-mystified. Photogrammetric Engineering and Remote Sensing, 52, 81-86.

Curran, P. J., 1980, Multispectral remote sensing of vegetation amount. Progress in Physical Geography, 4, 315-341.

Curran, P.J., 1981, Multispectral remote sensing for estimating biomass and productivity. In Smith, H. (ed.) Plants and the Daylight Spectrum (Academic Press, London), 65-99.

Curran, P. J., 1983, Problems in the remote sensing of vegetation canopies for biomass estimation. In Fuller, R. ed., Ecological Mapping from Ground, Air and Space, ITE Symposium no. 10, (NERC (ITE), Cambridge), 84-100.

Curran, P. J., 1985, Principles of Remote Sensing. (Longman, Essex).

Curran, P. J., 1986a, Multispectral air photography and its use for estimating green leaf area index. NERC News Journal, 3, 11-13.

Curran, P.J., 1986b, The use of small-format, light aircraft photography to estimate the green leaf area index of pteridium. In Smith, R.T. and Taylor, J.A., Bracken: Ecology, Land Use and Control Technology, (Parthenon, Carnforth), 57-64.

Curran, P.J., and Hay, A.M., 1986, The importance of measurement error for certain procedures in remote sensing at optical wavelengths. Photogrammetric Engineering and Remote Sensing, 52, 229-241.

Curran, P. J. and Milton, E. J., 1983, The relationships between the chlorophyll concentration, LAI and reflectance of a simple vegetation canopy. International Journal of Remote Sensing, 4, 247-256.

Curran, P. J. and Plummer, S. E., 1985, Preliminary report on the ecological and agricultural user requirements for remotely sensed data in the 1990s. Unpublished report for Polar Platform Land Applications Panel, University of Sheffield.

Curran, P.J. and Williamson, H.D., 1985, The accuracy of ground data used in remote sensing investigations. International Journal of Remote Sensing, 6, 1637-1651.

Curtis, L.F., 1984, Inventory and monitoring of National Park landscapes. Proceedings of a conference, Integrated Approaches in Remote Sensing, ESA SP-214, 349-352.

Curtis, L. F. and Walker, A. J., 1982, Moorland Conservation on Exmoor: the Porchester maps, their construction and policies. (Exmoor National Park, Dulverton).

Daultrey, S., 1976, Principal Components Analysis. Concepts and Techniques in Modern Geography no. 8. (Geo books, Norwich).

Dave, J. V., 1981, Influence of illumination and viewing geometry and atmospheric composition of the tasseled cap transformation of Landsat MSS data. Remote Sensing of Environment, 11, 37-55.

Dean, M. E. and Hoffer, R. M., 1983, Feature selection methodologies using simulated Thematic Mapper data. International Symposium on Machine Processing of Remotely Sensed data, (Purdue University, Lafayette), 347-356.

Department of Environment, 1974, Report of the National Park Policies Review Committee. (HMSO, London).

Desachy, J., Begni, G., Boisson, B. and Perbos, J. 1985, Investigation of Landsat-4 Thematic Mapper line-to-line and band-to-band registration and relative detector calibration. Photogrammetric Engineering and Remote Sensing, 51, 1291-1298.

Donoghue, D.N.M. and Hook, S.J.M., 1986, Preprocessing of airborne multi-spectral data, a necessity for quantitative remote sensing. Proceedings of the NERC 1985 Airborne Campaign Workshop, ITE Monkswood, Abbots Ripton, November 1986, (NERC (ITE), Cambridge), E-13 - E-17.

Duggin, M. J., 1980, The field measurement of reflectance factors. Photogrammetric Engineering and Remote Sensing, 46, 643-647.

Duggin, M. J., 1981a, Simultaneous masurement of irradiance and reflected radiance in field determination of spectral reflectance. Applied Optics 20, 3816-3818.

Duggin, M.J., 1981b, The need to use two radiometers simultaneously to make reflectance measurements in field conditions. Photogrammetric Engineering and Remote Sensing, 47, 142-144.

Duggin, M. J., 1985, Factors limiting the discrimination and quantification of terrestrial features using remotely sensed radiance. International Journal of Remote Sensing, 6, 3-27.

Dower, J., 1945, National Parks in England and Wales. Cmnd 6628 (HMSO, London).

Engel, J. L., and Weinstein, O., 1983, The Thematic Mapper - an overview. IEEE Transactions on Geoscience and Remote Sensing, GE-21, 258-265.

Everitt, J. H., Richardson, A. J., Gausman, H. W., 1985, Leaf reflectance -nitrogen - chlorophyll relations in buffelgrass. Photogrammetric Engineering and Remote Sensing, 51, 463-466.

Ferns, D. C., Zara, S.J. and Barber, J., 1983, Application of high resolution spectroradiometry to the remote sensing of vegetation. In Field Radiometry, Proc. Meeting of Remote Sensing Society and Royal Society of Chemistry, (Remote Sensing Society, Reading).

Ferns, D. C. and Barber, J., 1981, Leaf optics, asymptotic reflectance and canopy modelling - a review. (Plant Physiology Research, Dept. of Pure and Applied Biology, Imperial College, London).

Fischel, D., 1984, Validation of the Thematic Mapper Radiometric and Geometric Correction Algorithms. IEEE Transactions on Geoscience and Remote Sensing, GE-22, 237-242.

Forshaw, M. R. B., Haskell, A., Miller, P. F., Stanley, D. J., Townshend, J. R. G., 1983, Spatial resolution of remotely sensed imagery. International Journal of Remote Sensing, 4, 479-520.

Frank, T.D., 1984, Assessing change in the surficial character of a semi-arid environment with Landsat residual images. Photogrammetric Engineering and Remote Sensing, 50, 471-480.

Freden, S. C. and Gordon, F., 1983, Landsat Satellites. In Colwell, R.N. ed., Manual of Remote Sensing, 2nd edition, (American Society for Photogrammetry, Falls Church), 517-570.

Fusco, L., Frei, U., Trevese, D., Blonda, P.N., Pasquaviello, G., Milillo, G., 1986, Landsat TM image forward/reverse scan banding: characterisation and correction. International Journal of Remote Sensing, 7, 557-576.

Gates, D. M., 1970, Physical and physiological properties of plants. In Remote Sensing with Special Reference to Agriculture and Forestry. (Nat. Acad. of Sci., Washington D.C.), 224-252.

Gates, D. M., Keegan, H.J., Schleter, J.C., and Weidiner, V. P., 1965, Spectral properties of plants. Applied Optics, 4, 11-20.

Gausman, H. W., 1974, Leaf reflectance of near infrared. Photogrammetric Engineering and Remote Sensing, 40, 183-192.

Gausman, H. W., 1982, Visible light reflectance, transmittance and absorptance of differently pigmented cotton leaves. Remote Sensing of Environment, 13, 233-238.

Gausman, H. W., Allen, W. A., Cardenas, R. and Richardson, A.J., 1970, Relation of light reflectance to histological and physical evaluations of cotton leaf maturity. Applied Optics, 9, 545-553.

Gausman, H. W., Allen, W. A. and Escobar, D. E., 1974, Refractive Index of plant cell walls. Applied Optics, 13, 109-111.

Gimingham, C. H., 1960, Biological flora of the British Isles, Calluna vulgaris (L.) Hull. Journal of Ecology, 48, 455-483

Gimingham, C. H., 1972, Ecology of Heathlands, (Chapman and Hall, London).

Grace, J., and Woolhouse, H. W., 1974, Physiological and mathematical study of growth and productivity of a Calluna-Sphagnum community. IV Model of growing Calluna. Journal of Applied Ecology, 11, 281-295.

Grant, S. A., 1968, Heather regeneration following burning - a survey. Journal of the British Grassland Society, 23, 26-33.

Grebowsky, G. J., 1975, Characteristics of digital multispectral scanner data. NASA Report no. X-563-75-169 GSFC. (NASA GSFC, Maryland).

Griffiths, G. H., and Collins, W. G., 1983, Mapping the greenness of semi-arid rangeland vegetation in Northern Kenya from Landsat digital data. In Remote Sensing for Rangeland Monitoring and Management (Remote Sensing Society, Reading), 108-122.

Gordon, F., 1983, The time space relationships among data points from multispectral spatial scanners. International Journal of Remote Sensing, 4, 555-570.

H. M. Government, 1981 and 1985, Wildlife and Countryside Act. (HMSO, London).

Hardisky, M. A., Smart, R. M. and Klemas, V., 1983, Growth response and spectral characteristics of a short Spartina alterniflora salt marsh irrigated with freshwater and sewage effluent. Remote Sensing of Environment, 13, 57-67.

Hardy, D. D., Lodge, D. W. S., Thomas, I. L., 1987, The UK Columbus Programme. International Journal of Remote Sensing, 8, 217-219.

Harris, R. and Weaver, R. E., 1985, Vegetation discrimination in the North York Moors: an assessment of multi-temporal SPOT simulation data. Final report to National Remote Sensing Centre on research conducted as part of the 1984 SPOT simulation campaign.

Hatfield, J. L., Kanemasu, E. T., Asrar, G., Jackson, R. D., Pinter, P. J., Reginato, R. J. and Idso, S. B., 1985, Leaf Area estimates from spectral measurements over various planting dates of wheat. International Journal of Remote Sensing, 6, 169-175.

Henderson, F.B., 1984, Commercialization of satellite remote sensing worldwide. (Geosat Committee, San Francisco)

Henderson, K. E. and Badhwar, G. D., 1984, An initial model for estimating soybean development stages from spectral data. Remote Sensing of Environment, 14,

Hielkema, J. U., Rofey, J. and Tucker, C. J., 1986, Assessment of ecological conditions associated with the 1980/81 desert locust plague upsurge in Africa using environmental satellite data. International Journal of Remote Sensing, 7, 1609-1622.

HMSO, 1984, Remote Sensing and Digital Mapping. House of Lords Select Committee on Science and Technology. Session 1983-1984. First report vol I.

Holben, B.N., Schutt, J.B. and McMurtrey J., 1983, Leaf water stress detection utilizing Thematic Mapper bands 3,4 and 5 in soybean plants. International Journal of Remote Sensing, 4, 289-297.

Holmes, R. A., 1982, Advanced sensor systems: Thematic Mapper and beyond. 8th International Symposium on Machine Processing of Remotely Sensed data. (Purdue University, Lafayette), 540-545.

Horler, D. N. H., Barber, J. and Barringer, A. R., 1980, Effects of heavy metals on the absorbance and reflectance spectra of plants. International Journal of Remote Sensing, 1, 121-136.

Horler, D. N. H, Dockray, M. and Barber, J., 1983, The red edge of plant leaf reflectance. International Journal of Remote Sensing, 4, 273-288.

Hughes Aircraft Company, 1972, Multispectral scanner system for ERTS. Four band scanner system. Final report, NASA contract NS 5-11255 Vol. 1. System description and performance. NASA CR-132758.

Hume, E., McMorrow, J., Southey, J., 1986, Mapping semi-natural grassland communities from panchromatic aerial photographs and digital images at SPOT wavelengths. Archives of Photogrammetry and Remote Sensing, 26, 386-395.

Imeson, A. C., 1971, Heather burning and soil erosion on the North York Moors. Journal of Applied Ecology, 8, 537-542.

Jackson, R.D. and Ezra, C.E., 1985, Spectral response of cotton to suddenly induced water stress. International Journal of Remote Sensing, 6, 177-185.

Jensen, J. R., Hodgson, M. E., Christensen, E., Mackey, H. E., Tinney, L. R. and Sharitz, R., 1986, Remote sensing inland wetlands: a multispectral approach. Photogrammetric Engineering and Remote Sensing, 52, 87-100.

Justice, C. O. and Hiernaux, P. H. Y., 1986, Monitoring the grasslands of the Sahel using NOAA AVHRR data: Niger 1983. International Journal of Remote Sensing, 7, 1475-1498.

Kaufman, Y. J., 1985, The atmospheric effect on the separability of field classes measured from satellites. Remote Sensing of Environment, 18, 21-34

Kauth, R. J. and Thomas, G. S., 1976, The tasseled cap - A graphic description of the spectral-temporal development of agricultural crops as seen by Landsat. 2nd International symposium on Machine Processing of Remotely Sensed Data. (Purdue University, Lafayette), 4B-41 - 4b-49.

Kayll, A. J. and Gimingham, C. H., 1965, Vegetative regeneration of Calluna vulgaris after fire. Journal of Ecology, 53, 729-734.

Kimes, D. S., 1983, Dynamics of directional reflectance factor distributions for vegetation canopies. Applied Optics, 22, 1364-1372.

King, D., 1987, Sensors for Imaging. Space, 3, 17-21.

Kirchner, J. A., Schnetzler, C. C. and Smith, J. A., 1981, Simulated directional radiances of vegetation from satellite platforms. International Journal of Remote Sensing, 2, 253-264.

Kirchner, J. A., Kimes, D. S., McMurtrey, J. E., 1982, Variation of directional reflectance factors with structural changes of a developing alfalfa canopy. Applied Optics, 21, 3766-3774.

Knipling, E. B., 1970, Physical and physiological basis for the reflectance of visible and near-infrared radiation from vegetation. Remote Sensing of Environment, 1, 155-159.

Kowalik, W. S. and Marsh, S. E., 1982, A relation between Landsat digital numbers, surface reflectance and cosine of solar zenith angle. Remote Sensing of Environment, 12, 39-55.

Krinov, E. L., 1947, Speltra'naia Otrazatel'naia Sposobnost' Prirodrykh Obrazovanii (Spectral reflectance properties of natural formations). Laboratoriaa Aerometodov, Akad. Nauk USSR, Moscow.

Lansing, J. C. and Cline, R. W., 1975, The four and five band multispectral scanners for Landsat. Optical Engineering, 14, 312-322.

Lintz, J. and Simonett, D. S., 1976, Remote Sensing of Environment. (Addison Wesley, Reading Mass.)

Lynn, D. W., 1984, Surface material mapping in the English fenlands using airborne multi-spectral scanner data. International Journal of Remote Sensing, 5, 699-714.

MacDonald, R. B., 1984, A summary of the history of the development of automated remote sensing for agricultural applications. IEEE Transactions on Geoscience and Remote Sensing, GE-22, 473-482.

MacEwen, A. and MacEwen, M., 1983, National Parks: Conservation or Cosmetics ? (Allen and Unwin, London).

Malila, W. A., Metzler, M. D., Rice, D. P. and Crist, E. P., 1984, Characterisation of Landsat-4 MSS and TM Digital Image Data. IEEE Transactions on Geoscience and Remote Sensing, GE-22, 177-191.

Maltby, E., 1980, The impact of severe fire on Calluna moorland in the North York Moors. Bulletin of Ecology, 11, 683 - 708

Markham, B.L. and Barker, J.L., 1980, Earth Survey Applications Divisiion Report. NASA-Goddard Space Flight Centre. TM 806 42 8-49.

Markham, B. L. and Barker, J. L., 1983, Spectral characterisation of the Landsat-4 MSS sensors. Photogrammetric Engineering and Remote Sensing, 49, 811-833.

Markham, B. L. and Barker, J. L., 1985, Spectral characterisation of the Landsat Thematic Mapper sensors. International Journal of Remote Sensing, 6, 697-716.

Midan, J. P., 1986, The SPOT-HRV instrument: an overview of design and performance. Earth-oriented Applications of Space Technology, 6, 163-172.

Miles, J., 1979, Vegetation Dynamics. Outline Studies in Ecology series. (Chapman and Hall, London).

Milton, E. J., 1980, A portable multiband radiometer for ground data collection in remote sensing. International Journal of Remote Sensing, 1, 153-165.

Milton, E. J., 1981, Does the use of two radiometers correct for irradiance changes during measurements? Photogrammetric Engineering and Remote Sensing, 47, 1223-1225.

Milton, E. J., 1982, Factors affecting the multispectral response of vegetated surfaces. Unpublished Ph. D. thesis, University of Reading.

Milton, E. J., Gurnell, A. M. and Clark, M. J., 1986, Heathland vegetation survey and hydrological mapping from simulated SPOT HRV data. Final report to the National Remote Sensing Centre on research conducted as part of the 1984 SPOT simulation campaign.

Miller, G. R. and Miles, J., 1970, Regeneration of Calluna vulgaris at different ages and seasons in N. E. Scotland. Journal of Applied Ecology, 7, 51-60.

Ministry of Town and Country Planning, 1947, Report of the National Parks Committee (England and Wales). Cmnd 7121, (HMSO, London).

Ministry of Works and Planning, 1942, Report of the Committee on Land Utilisation in Rural Areas. (HMSO, London).

Morton, A., 1986, Moorland plant community recognition using Landsat MSS data. Remote Sensing of Environment, 20, 291-298.

Munday, J.C., 1983, Chromaticity of path radiance and atmospheric correction of Landsat data. Remote Sensing of Environment, 13, 525-538.

Murphy, J. M., Butlin, T., Duff, P. F. and Fitzgerald, A. J., 1984, Revised radiometric calibration technique for LANDSAT-4 Thematic Mapper data. IEEE Transactions on Geoscience and Remote Sensing, GE-22, 243-250.

NASA, 1967a, Earth photographs from Gemini 3,4,5. NASA SP-129

NASA, 1967b, Terrain photography on the Gemini IV mission: preliminary report. NASA TND-3982.

NASA, 1978, Independent peer evaluation of the Large Area Crop Inventory experiment (LACIE). Proc. of Plenary Session. NASA JSC-14550, JSC-14551, JSC-16015. (NTIS, Springfield Va).

NASA, 1984a, The Global Habitability Programme. NASA publicity leaflet.

NASA, 1984b, Imaging Spectrometry: the next step in remote sensing. NASA JPL 400-243 9/84. (NASA JPL, Pasadena Calif.)

NASA, 1984c, Earth Observing System: Science and Mission Requirements. Working Group Report Vol 1. NASA TM-86129.

Nichol, J. E., 1983, Remote Sensing of Fuelwood Resources in Nigeria Savanna. In Remote Sensing for Rangeland Monitoring and Management, (Remote Sensing Society, Reading), 25-35.

North York Moors National Park, 1979, Geology of the North York Moors. (NYMNP, Helmsley).

North York Moors National Park, 1981a, Consultation Paper: Nature Conservation in the North York Moors National Park. (NYMNP, Helmsley).

North York Moors National Park, 1981b, Patterns of Informal Recreation in the North York Moors National Park. (NYMNP, Helmsley).

North York Moors National Park, 1982, Discussion Paper: The Future of the Moorland. (NYMNP, Helmsley).

North York Moors National Park, 1986, Moorland Management. (NYMNP, Helmsley).

Norton, A. J., 1982, Bracken management on the North York Moors. Unpublished M.Sc thesis, Wye College.

Norwood, V. and Lansing, J. C., 1983, Electo-optical imaging sensors. In Colwell R. N. ed., Manual of Remote Sensing, 2nd edition, (American Society for Photogrammetry and Remote Sensing, Falls Church), 325-367.

Odenweller, J.B. and Johnson, K.I., 1984, Crop identification using Landsat temporal-spectral profiles. Remote Sensing of Environment, 14, 39-54.

Otterman, J. and Robinove, C. J., 1981, Effects of the atmosphere on the detection of surface changes from Landsat MSS data. International Journal of Remote Sensing, 2, 351-360.

Oxley, E. R. B. and Williams, J. H., 1985, Remote sensing of grassland fertility. In Cooper, J. P. and Raymond, W. F. ed., Grassland Manuring. British Grassland Society Occasional Symposium no. 20, 97-101.

Palmer, J. M., 1984, Effective bandwidths for Landsat-4 and Landsat-D' Multispectral Scanner and Thematic Mapper subsystems. IEEE Transactions on Geoscience and Remote Sensing, GE-22, 336-338.

Palmer, J. M. and Tomasko, M. G., 1980, Broadband radiometry with spectrally selective detectors. Optics Letters, 5, 208-210.

Pardoe, G., 1985, EURECA: The reusable satellite emerges. Space, 1, 34-37.

Parry, M., Bruce, A. and Harkness, C., 1981, The plight of British moorlands. New Scientist 23.7.81. 550-551

Parry, M., Bruce, A. and Harkness, C. E., 1982, Changes in the extent of moorland and roughland in the North York Moors. Surveys of moorland and roughland change no. 5. Dept. of Geography, University of Birmingham.

Pinter, P. J., Jackson, R. D., Idso, S. B. and Reginato, R. J., 1981, Multidate spectral reflectance as predictors of yield in water stressed wheat and barley. International Journal of Remote Sensing, 2, 43-88.

Pinter, P. J., Jackson, R. D., Idso, S. B. and Reginato, R. J, 1983, Diurnal patterns of wheat spectral reflectances. IEEE Transactions on Geoscience and Remote Sensing, GE-21, 156-163.

Piwinski, D. J., Schoch, L. B., Duggin, M. J. and Whitehead, V., 1983, Dependence of NOAA-AVHRR recorded radiance on scan angle, atmospheric turbidity and unresolved cloud. 17th International Symposium on Remote Sensing of Environment, (Michigan University, Ann Arbor), 1-10.

Popper, K., 1974, The problem of induction. In Schilpp, P. A. ed., The Philosophy of Karl Popper, (La Salle, Illinois), 1013-1023.

Poros, D. J. and Peterson, C. J., 1985, Methods for destriping Landsat Thematic Mapper images - a feasibility study for an online destriping process in the Thematic Mapper Image Processing System (TIPS). Photogrammetric Engineering and Remote Sensing, 51, 1371-1378.

Potter, J. F., 1972, Response of the ERTS Multispectral Scanner. Lockheed Electronics Company TM 642-044, Houston, Texas.

Potter, J. M. and Shelton, M., 1974, Effect of atmospheric haze and sun angle on automatic classification of ERTS-1 data. 9th International Symposium on Remote Sensing of Environment, (University of Michigan, Ann Arbor)

Price, J. C., 1981, The contribution of thermal data in Landsat multispectral classification. Photogrammetric Engineering and Remote Sensing, 47, 229-236.

Price, J. C., 1984, Comparison of the information content of data from the LANDSAT-4 Thematic Mapper amd the Multispectral Scanner. IEEE Transactions on Geoscience and Remote Sensing, GE-22, 272-281.

Price, J. C., 1986, Comments on evaluations of simulated SPOT data. Photogrammetric Engineering and Remote Sensing, 52, 272-281.

Puritch, G. S., 1981, Nonvisual remote sensing of trees affected by stress. Forestry Technical Report 30, Canadian Forestry Service, Pacific Forest Research Centre, Victoria, British Columbia.

Rao, R.G.S. and Ulaby, F.T., 1977, Optimal sampling techniques for ground truth data in microwave remote sensing of soil moisture. Remote Sensing of Environment, 6, 289-297

Richardson, A. J., 1981, Measurement of reflectance factors under daily and intermittent irradiance variations. Applied Optics, 20, 3336-3340.

Richardson, A. J., Everitt, J. H. and Gausman, H. W., 1983, Radiometric estimation of biomass and Nitrogen content of Alicia grass. Remote Sensing of Environment, 13, 179-184.

Richardson, A.J. and Wiegand, R. 1977, Distinguishing vegetation from soil background. Photogrammetric Engineering and Remote Sensing, 43, 1541-1552.

Richardson, A. J., 1975, Plant soil and shadow reflectance components of row crops. Photogrammetric Engineering and Remote Sensing, 41, 1401-1407.

Richter, R., 1985, Some aspects of the atmospheric radiance model of LOWTRAN 6. International Journal of Remote Sensing, 6, 1773-1777.

Ripple, W. J., 1985a, Landsat Thematic Mapper bands for characterizing fescue vegetation. International Journal of Remote Sensing, 6, 1373-1384.

Ripple, W. J., 1985b, Asymptotic reflectance characteristics of grass vegetation. Photogrammetric Engineering and Remote Sensing, 51, 1915-1921.

Ripple, W. J., 1986, Spectral reflectance relationships to leaf water stress. Photogrammetric Engineering and Remote Sensing, 52, 1669-1676.

Rogers, A., Blunden, J. and Curry, N. ed., 1985, The Countryside Handbook. (Open University and Croom Helm, Milton Keynes).

Price, J.C., 1987, Calibration of satellite radiometers and the comparison of vegetation indices. Remote Sensing of Environment, 21, 15-27

Rose, P. W. and Rosendahl, P. C., 1979, An application of Landsat Multispectral imagery for the classification of hydrobiological systems, Shark River Slough, Everglades National Park, Florida. South Florida Research Centre Report T-544.

Roy, P. S., Kaul, R. N., Sharma Roy, M. R. and Garbyal, S., 1985, Forest-type stratification and delineation of shifting cultivation areas in the eastern part of Arunaci Pradesh using Landsat MSS data. International Journal of Remote Sensing, 6, 411-418.

Royer, A., Vincent, P. and Bonn, F., 1985, Evaluation and correction of viewing angle effects on satellite measurements of bidirectional reflectance. Photogrammetric Engineering and Remote Sensing, 51, 1895-1914.

Saint, G. and Weill, G., 1984, SPOT simulation methodology, simulated vs. satellite image parameters. In SPOT Simulations Applications Handbook. Proc. of the 1984 SPOT symposium, Scottsdale, Arizona, (American Socety for Photogrammetry and Remote Sensing, Falls Church), 19-28.

Salman, A. B., 1983, Using Landsat imagery interpretation for underground water prospection around Qena Province, Egypt. International Journal of Remote Sensing, 4, 179-191.

Salomonson, V. V., Smith, P. L., Park, A. B., Webb, W. C. and Lynon, T. J., 1980, An overview of progress in the design and implementation of Landsat-D systems. IEEE Transactions on Geoscience and Remote Sensing, GE-18, 137-146.

Salomonson, V. V. and Park, A., 1979, An overview of the Landsat-D project with emphasis on the flight segment. 5th International Symposium on Machine Processsing of Remotely Sensed Data, (Purdue University, Lafayette), 2-11.

Schneider, S. R., McGinnis Jr., D. F. and Stephens, G., 1985, Monitoring Africa's Lake Chad Basin with Landsat and NOAA satellite data. International Journal of Remote Sensing, 6, 59-74.

Schutt, J. B., Rowland, R. R. and Heartly, W. H., 1984, A laboratory investigation of a physical mechanism for the extended infrared absorption ('red shift') in wheat. International Journal of Remote Sensing, 5, 95-101.

Schwaller, M. R., Benninghof, W. S. and Olson, C. E., 1984, Prospects for satellite remote sensing of Adelie penguin rookeries. International Journal of Remote Sensing, 5, 849-853.

Sellers, P. J., 1985, Canopy reflectance, photosynthesis and transpiration. International Journal of Remote Sensing, 6, 1335-1372.

Silk, J., 1981, The analysis of Variance. Concepts and Techniques in Modern Geography no. 30. (Geobooks, Norwich)

Simmons, I. G., Atherden, M. A., Cundill, P. R., Innes, J. B. and Jones, R. L., 1982, Prehistoric Environments. In Spratt, D. A. ed., Prehistoric and Roman Archaeology of North-East Yorkshire. Brit. Arch. Reports, British Series 104. (BAR, Oxford).

Simonett, D. S., 1983, The Development and Principles of Remote Sensing. In Colwell, R. N. ed., Manual of Remote Sensing, 2nd edition. (American Socety for Photogrammetry and Remote Sensing, Falls Church), 1-35.

Singh, A., 1985, Thematic Mapper radiometric correction research and development results and performance. Photogrammetric Engineering and Remote Sensing, 51, 1379-1383.

Singh, A. and Harrison, A., 1985, Standardized principal components. International Jouranl of Remote Sensing, 6, 883-896.

Slater, P. N., 1979, A re-examination of the Landsat MSS. Photogrammetric Engineering and Remote Sensing, 45, 1479-1485.

Slater, P. N., 1980, Remote Sensing: Optics and optical systems. (Addison-Wesley, Reading Mass.).

Slater, P. N., 1983, A review of some radiometric calibration problems and methods. Proc. International Colloquium on Spectral Signatures of objects in remote sensing, Bordeaux, (INRA), 391-405.

Slater, P. N., 1985, Survey of Multispectral Imaging Systems for Earth Observations. Remote Sensing of Environment, 17, 85-102.

Slater, P. N. and Jackson, R. D., 1982, Atmospheric affects on radiation reflected from soil and vegetation as measured by orbital sensors using various scanning directions. Applied Optics, 21, 3923-3931.

Steven, M. D. and Rollin, E. M., 1986, Estimation of atmospheric corrections from multiple aircraft imagery. International Journal of Remote Sensing, 7, 481-498.

Sugden, D. and Birnie, J., 1983, Research Design and Postgraduate Research in Geomorphology. Discussion Paper no. 5. Dept. of Geography, University of Aberdeen.

Swain, P. H. and Davis, S. M., 1978, Remote Sensing: the Quantitative Approach. (McGraw-Hill, New York).

Swain, P. H. and King, R. C., 1973, Two effective selection criteria for Multispectral remote sensing. Proceedings of the First International Colloquium on Pattern Recognition, Piscataway. IEEE Cat. no. 73CHO82 1-96, 536-540.

Swain, P. H., Vanderbilt, V. C. and Johnson, C. D., 1982, A quantitative applications-oriented evaluation of Thematic Mapper design specifications. IEEE Transactions on Geoscience and Remote Sensing, GE-20, 370-377.

Tarran, A. E., 1985, Evaluation of SPOT satellite simulation imagery for mapping and monitoring hill land improvement. Final report to National Remote Sensing Centre on research conducted as part of the 1984 SPOT simulation campaign.

Thiruvengadachari, S., 1983, Remote sensing of tank irrigated areas in Tamil Nadu state, India. International Journal of Remote Sensing, 4, 545-554.

Townshend, J. R. G., ed., 1981a, Terrain Analysis and Remote Sensing. (George Allen and Unwin, London).

Townshend, J. R. G., 1981b, The spatial resolving power of earth resources satellites. Progress in Physical Geography, 5, 33-51.

Townshend, J. R. G., 1984, Agricultural land cover discrimination using Thematic Mapper spectral bands. International Journal of Remote Sensing, 5, 681-698.

Townshend J. R. G. and Harrison, A., 1984, Estimation of the resolving power of the Thematic Mapper of Landsat 4. In Satellite Remote Sensing - Retrospect and Prospect, (Remote Sensing Society, Reading), 67-72.

Townshend, J. R. G., Gayler, J. E., Hardy, J. R., Jackson, M. J. and Baker, J. R., 1983, Preliminary analysis of Landsat-4 Thematic Mapper products. International Journal of Remote Sensing, 4, 817-828.

Townshend, J.R.G. and Justice, C.O., 1980, Unsupervised classification of remotely sensed data for mapping spatially complex vegetation. International Journal of Remote Sensing, 1, 105-120.

Tucker, C. J., 1977a, Spectral estimation of grass canopy variables. Remote Sensing of Environment, 6, 11-26.

Tucker, C. J., 1977b, Asymptotic nature of grass canopy spectral reflectance. Applied Optics, 16, 1151-1156.

Tucker, C. J., 1978, A comparison of satellite sensor bands for vegetation monitoring. Photogrammetric Engineering and Remote Sensing, 44, 1369-1380.

Tucker, C. J., 1979, Red and Photographic infrared linear combinations for monitoring vegetation. Remote Sensing of Environment, 8, 127-150.

Tucker, C. J., 1980a, Remote sensing of leaf water content in the near infrared. Remote Sensing of Environment, 10, 23-32.

Tucker, C. J., 1980b, Radiometric resolution for monitoring vegetation. How many bits are needed ? International Journal of Remote Sensing, 1, 241-254.

Tucker, C. J., Miller, D. L. and Pearson, R. L., 1975, Shortgrass prairie spectral measurements. Photogrammetric Engineering and Remote Sensing, 41, 1157-1162.

Tucker, C. J. and Maxwell, E. L., 1976, Sensor design for monitoring vegetation canopies. Photogrammetric Engineering and Remote Sensing, 42, 1399-1410.

Tucker, C. J. and Miller, L. D., 1977, Soil spectra contributions to grass canopy spectral reflectance. Photogrammetric Engineering and Remote Sensing, 43, 721-726.

United States Geological Survey (USGS), 1982, Landsat 4 Data Users Handbook. (USGS, Alexandria Va.).

Vanderbilt, V. C., Stoner, E. R., Biehl. L. L., Robinson, B.F., Weismiller, A., Bauer, M. E., 1980, Fine structure in the spectral reflectance of vegetation and soils. 6th International Symposium on Machine Processing of Remotely Sensed Data, (Purdue University, Lafayette), 358 (abstract only).

Walker, R. E., Zobrist, A. L., Bryant, N. A., Gokhman, B., Friedman and Logan, T. L., 1984, An analysis of Landsat-4 Thematic Mapper geometric properties. IEEE Transactions on Geoscience and Remote Sensing, GE-22, 288-293.

Wardley, N. W. and Milton, E. J., 1985, Remote sensing of structurally complex semi-natural vegetation. Preliminary results from lowland heath. Unpublished report, Dept. of Geography, University of Southampton.

Wardley, N. W., Milton, E. J. and Hill, C. T., 1987, Remote sensing of structurally complex semi-natural vegetation - an example from heathland. International Journal of Remote Sensing, 8, 31-42.

Watt, A. S., 1955, Bracken versus heather, a study in plant sociology. Journal of Ecology, 43, 490-506

Weaver, R.E., Use of remote sensing to monitor bracken encroachment in the North York Moors. In Smith, R.T. and Taylor, J.A., Bracken:Ecology, Land Use and Control Technology. (Parthenon, Carnforth), 65-76.

Weaver, R.E. and Wright, R., 1986, The use of multispectral airborne scanner data for mapping upland vegetation. Proceedings of the NERC 1985 Airborne Campaign Workshop held at ITE Monkswood, Abbots Ripton, November 1986. (NERC, Cambridge), A-27 - A-40.

Whittaker, R. E. and Gimingham, C. H., 1962, The effect of fire on regeneration of Calluna vulgais (L.) hull from seed. Journal of Ecology, 50, 815-822.

Williams, D. F., 1984, Overview of the NERC airborne Thematic Mapper campaign of September 1982. International Journal of Remote Sensing, 5, 631-634.

Williams, D. L., Irons, J. R., Markham, B. L., Nelson, R. F., Toll, D. L., Latty, R. S. and Stauffer, M. L., 1984, A statistical evaluation of the advantages of LANDSAT Thematic Mapper data in comparison to Multispectral Scanner Data. IEEE Transactions on Geoscience and Remote Sensing, GE-22, 294-302.

Williams, W. T., Lambert, J. M. and Lance, G. N., 1966, Multivariate methods in plant ecology. V. Similarity analyses and information analysis. Journal of Ecology, 54, 427-445.

Wilson, A., 1986, Calibration of ATM data. Proc. NERC 1985 Airborne Campaign workshop, ITE Monkswood, Abbots Ripton, November 1986 (NERC, Cambridge), E-25 - E-40.

Wooding, M. G., 1983, Crop mapping across different soil types in East Anglia using Landsat MSS data. Results of the Agrispine Experiment. Proc. meeting entitled Agrispine '82, An experiment in time dependent applications of satellite remote sensing data. Convened by the Remote Sensing Society at the Royal Aircraft Establishment, Farnborough.

Wooding, M. G., 1985, SAR Image segmentation using digitised field boundaries for crop mapping and monitoring applications. Proc. EARSeL workshop 'Microwave Remote Sensing applied to vegetation', Amsterdam, December 1984. ESA SP-227, January 1985.

Wrigley, R. C., Card, D. H., Hlavka, C. A., Hall, J. R., Mertz, F. C., Archwamety, C. and Schowengerdt, R. A., 1984, Thematic Mapper image quality: registration, noise and resolution. IEEE Transactions on Geoscience and Remote Sensing, GE-22, 263-271.

Yool, S. R., Star, J.L., Estes, J. E., Botkin, D. B., Eckhardt, D. W. and Davis, F. W., 1986, Performance analysis of image processing algorithms for classification of natural vegetation in the mountains of southern California. International Journal of Remote Sensing, 7, 683-702.

APPENDICES

Exposed peat surface

1	2	3	4	5	6	7	8	9	10	11	12	13
1	-	-	25.3	-	-	-	7.2	-	56.7	2.6	8.3	39.5
2	-	16.9	19.1	-	-	-	-	-	54.0	2.7	7.4	126.6
3	1.6	14.6	23.4	-	-	-	-	-	54.2	-	6.3	299.8
4	-	40.7	15.9	-	-	-	0.5	-	30.2	7.9	5.3	71.0
5	1.6	25.0	27.1	-	-	-	1.1	-	44.2	-	2.7	37.8
6	-	52.9	8.7	-	-	2.9	-	-	25.2	-	10.2	272.0
7	-	12.7	23.9	-	-	-	-	-	46.7	6.6	10.2	15.9
8	-	51.0	16.8	-	-	-	-	-	20.9	2.6	8.7	247.8
9	-	61.9	15.3	-	-	-	-	-	17.5	-	5.3	146.4
10	-	13.2	19.8	-	-	-	-	-	55.8	-	11.2	146.8
11	7.9	18.5	11.1	-	13.2	18.0	-	-	16.4	0.5	14.3	83.1
12	-	43.4	19.6	-	-	-	-	-	24.9	-	12.2	165.9
$\bar{x}$	0.9	29.2	18.8	-	1.1	1.7	0.7	-	37.2	1.9	8.5	138.7
σ	2.3	19.8	5.6	-	3.8	5.2	2.1	-	16.1	2.8	3.3	91.0

Partially exposed peat surface

1	2	3	4	5	6	7	8	9	10	11	12	13
13	16.8	-	22.1	-	-	-	-	2.1	22.1	21.1	15.8	63.8
14	18.3	-	24.2	-	-	-	-	1.6	30.1	11.8	14.0	48.7
15	36.8	-	16.5	3.3	-	-	-	1.7	18.7	11.5	11.5	-
16	61.1	-	2.7	11.4	-	-	-	1.1	7.6	2.7	13.5	11.5
21	44.1	-	15.6	-	5.0	1.1	-	-	15.6	10.1	8.4	52.1
24	12.4	-	30.7	-	-	-	-	-	27.4	18.8	10.9	14.9
25	50.8	-	12.7	3.2	-	-	-	-	15.9	9.0	8.5	12.3
28	37.9	-	13.2	9.3	-	-	-	-	17.6	16.5	5.5	8.8
31	22.3	-	10.3	1.6	-	-	-	-	25.5	1.1	12.0	42.4
40	57.9	-	4.7	10.5	-	0.5	-	18.0	0.5	-	7.9	34.4
46	14.0	-	16.0	-	-	-	-	28.0	9.0	17.0	3.0	160.4
55	-	-	28.5	-	-	-	-	0.6	51.4			
$\bar{x}$	31.0	-	16.4	3.3	0.4	0.1	-	6.6	20.3	11.2	9.6	44.9
σ	19.8	-	6.7	4.5	1.4	0.3	-	10.7	13.1	7.0	4.0	42.7

Mature heather

1	2	3	4	5	6	7	8	9	10	11	12	13
43	51.7	25.8	-	9.3	-	-	-	-	-	-	13.2	66.8
44	70.4	1.1	-	14.5	-	1.1	-	-	-	-	12.9	97.8
45	70.4	1.7	-	14.5	-	1.1	-	-	-	-	12.9	360.9
47	51.4	8.0	-	25.1	-	-	-	-	-	-	15.5	-
48	66.7	5.8	-	-	13.8	-	-	-	-	-	13.8	79.9
49	78.9	5.4	-	9.0	-	-	-	-	-	-	6.6	78.8
51	74.3	0.6	-	11.2	-	-	-	-	-	-	13.9	108.3
52	43.9	22.0	-	16.8	0.6	-	-	-	-	-	16.8	228.7
53	56.6	18.3	-	9.7	0.6	-	-	-	-	-	14.9	73.2
54	44.4	42.8	-	6.1	-	-	-	-	-	-	6.7	71.3
56	74.6	2.8	-	9.0	-	-	-	-	-	-	13.6	81.1
57	69.4	11.7	-	5.0	-	-	-	-	-	-	13.9	59.9
$\bar{x}$	62.7	12.2	-	12.0	0.1	0.2	-	-	-	-	12.9	118.8
σ	12.4	12.8	-	5.4	0.2	0.4	-	-	-		3.1	88.6

Heather/sedges mix

1	2	3	4	5	6	7	8	9	10	11	12	13
32	39.8	30.0	-	4.0	10.2	1.1	3.4	-	-	-	11.4	489.1
33	48.0	13.0	-	5.1	6.2	12.4	-	-	-	-	15.3	188.5
50	23.3	-	-	10.2	29.6	14.2	-	-	-	-	22.7	301.9
58	21.9	-	-	7.8	28.7	20.3	-	-	-	-	17.2	378.4
59	20.1	-	-	3.8	31.0	25.0	1.6	-	-	-	20.1	722.4
60	40.1	1.1	-	14.8	9.9	2.8	-	-	8.8	-	22.5	422.9
61	43.1	15.9	-	9.6	5.9	5.3	-	-	0.5	-	20.7	167.2
62	38.5	15.0	-	9.6	3.7	1.6	6.4	-	-	-	25.1	240.6
63	42.9	10.4	-	17.0	9.9	4.6	-	-	-	-	14.8	371.1
64	29.3	3.1	-	4.2	30.4	12.6	-	-	-	-	20.4	-
65	50.6	25.9	-	4.8	1.2	4.8	-	-	-	-	12.7	188.5
66	40.8	22.3	-	9.8	9.8	1.6	-	-	-	-	15.8	549.2
$\bar{x}$	36.5	11.4	-	8.4	14.7	8.9	1.0	-	1.1	-	18.2	365.4
σ	10.3	10.8	-	4.3	11.6	8.0	2.0	-	2.7	-	4.3	165.6

Sedges

1	2	3	4	5	6	7	8	9	10	11	12	13
17	39.9	14.5	-	8.3	19.7	9.8	-	-	-	-	7.8	433.7
18	5.7	2.1	-	1.5	43.2	25.5	3.1	-	3.1	8.9	6.8	369.4
19	23.8	8.8	-	4.7	26.9	20.2	-	-	6.7	8.8	1.5	366.3
20	17.7	5.1	-	3.0	40.4	26.3	-	-	-	-	7.1	464.6
22	22.3	3.8	-	3.8	38.0	25.5	-	-	-	0.5	6.5	418.0
23	32.1	14.2	-	5.8	16.8	23.7	-	-	-	-	6.8	372.3
26	18.8	2.6	-	1.6	38.5	28.7	-	-	-	-	9.9	281.4
27	18.2	8.0	-	0.5	41.4	21.7	-	-	1.5	-	8.6	368.6
29	17.5	9.0	-	1.1	43.4	22.8	-	-	3.2	-	3.2	330.6
30	29.3	7.9	-	2.1	30.4	17.8	5.8	-	-	-	6.8	372.3
41	38.6	10.6	-	1.1	24.0	19.0	2.2	-	-	-	4.5	333.4
42	21.9	5.4	-	3.2	31.0	15.0	-	-	19.8	-	3.7	405.3
$\bar{x}$	23.8	7.6	-	3.0	32.8	21.3	0.9	-	2.9	1.6	6.1	376.3
σ	9.7	4.1	-	2.3	9.3	5.3	1.9	-	5.7	3.4	2.4	47.3

Appendix 1 table 1 Description of vegetation at radiometer test sites, August 1983. See text (chapter 4) for explanation.

Explanation of variables:

1 site number (arbitrary)
2 % cover green shoots - Calluna
3 % cover brown/woody material - Calluna
4 % cover recognisable (dead) fragments/stems of Calluna detached from main plant
5 % cover flowers - Calluna
6 % cover green shoots -Eriophorum
7 % brown material - Eriophorum
8 % cover mosses
9 % cover Vaccinium
10 % cover litter
11 % cover soil
12 % cover shadow
13 soil moisture - as % dry weight
moisture

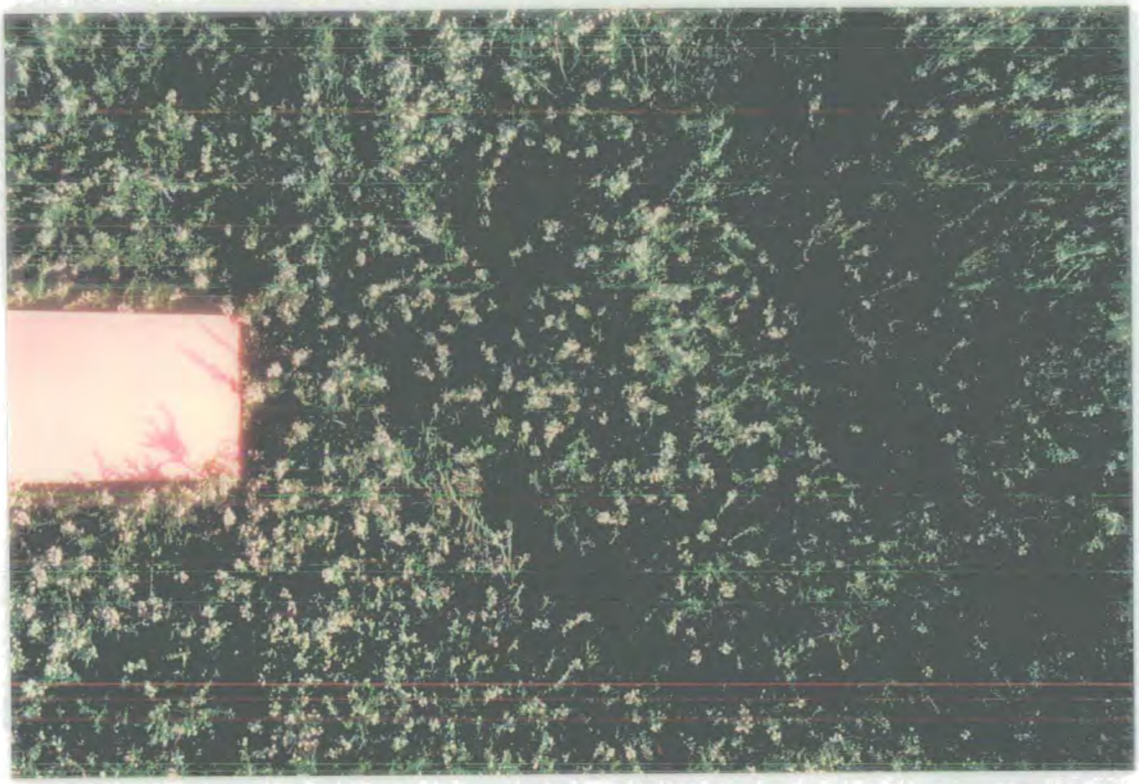
Appendix 1 figure. Examples of each vegetation type - from vertical colour transparency. Red book (removed during radiometer readings) c. 15cms long.

site 9

site 10

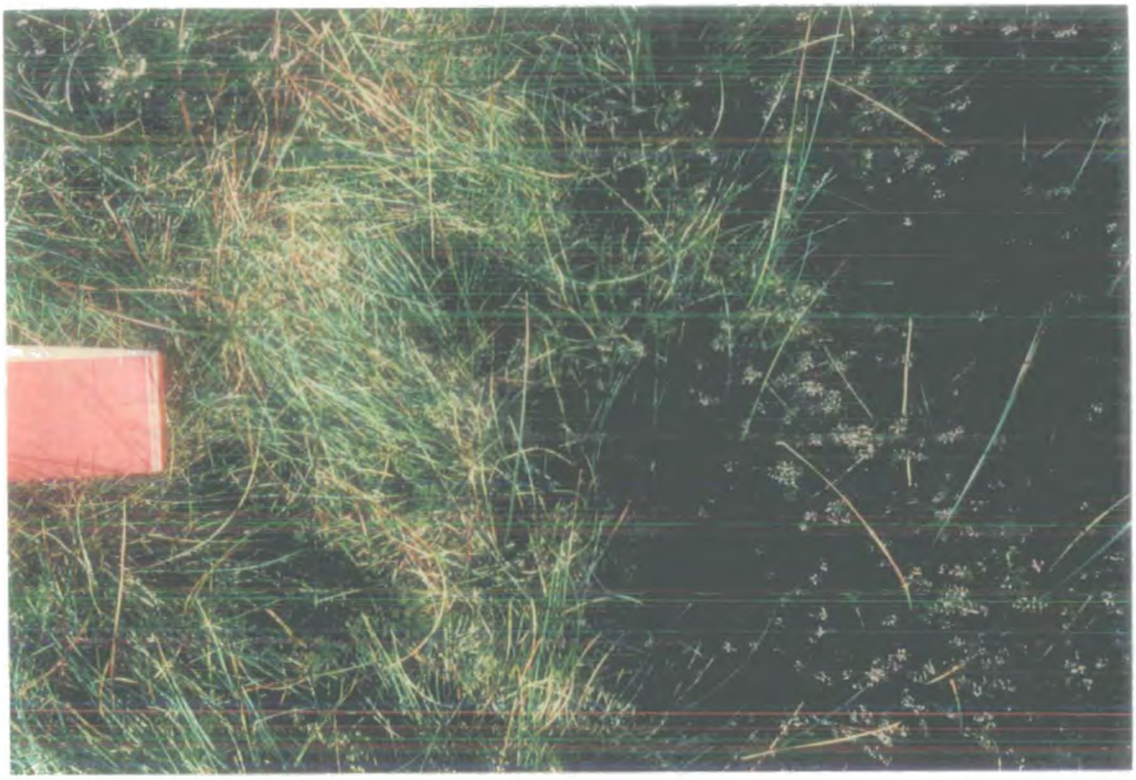
site 46

site 13



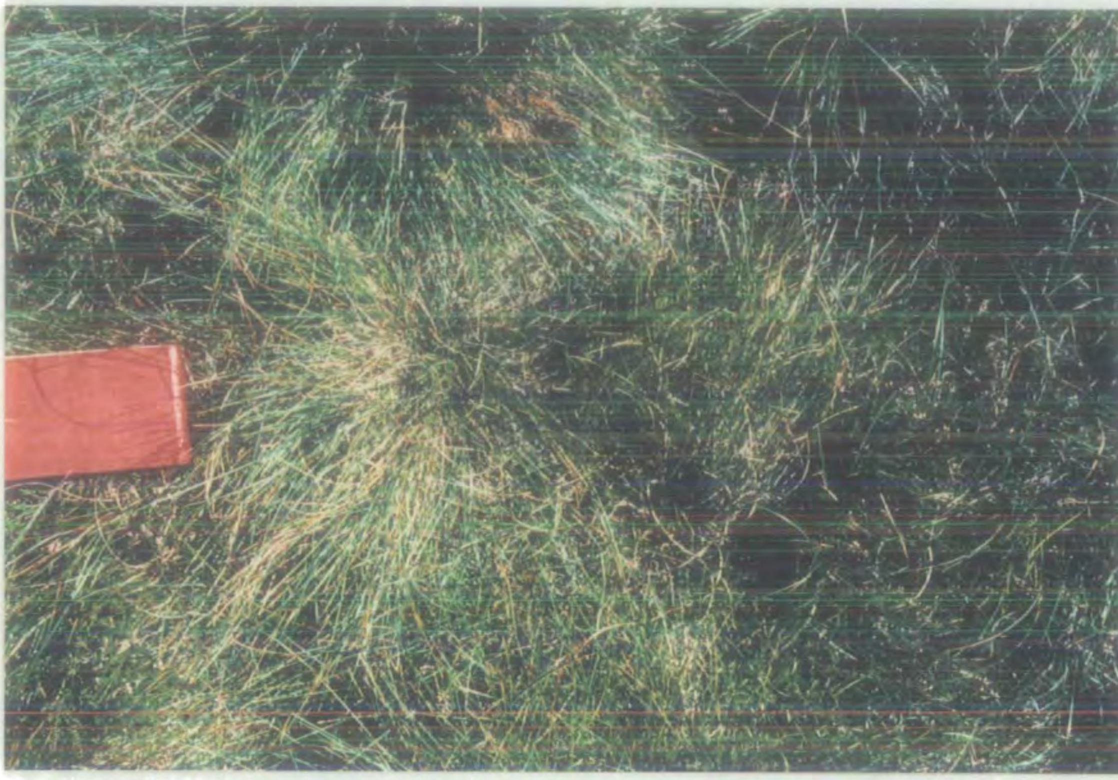
site 51

site 57



site 59

site 65



site 27

site 18

Site No.	August 1983	Sept. 1984	May 1984 line 1	May 1984 line 5
1	x	x	x	-
2	d	d	-	-
3	d	d	-	-
4	x	x	-	x
5	x	x	-	x
6	x		-	x
7	x	x	-	x
8	d	d	x	-
9	x	x	x	-
10	x	x	-	x
11	d	d	-	-
12	x	x	-	x
13	d	d	-	-
14	x	x	-	x
15	d	d	-	-
16	d	d	-	-
17	x	x	x	-
18	x	x	x	-
19	x	-	x	-
20	x	-	-	-
21	d	x	x	x
22	x	x	-	-
23	x	x	x	-
24a	-	x	x	x
24b	-	x	-	-

Appendix 2: Table 2 Test sites used in analysis of ATM data. Sites denoted d were discarded from analysis as their spectral characteristics are effectively duplicates of other sites in the group. Sites marked - were unavailable in the data shown because of their position relative to the flight line.

Site	XS 1 $\bar{x}$	XS 1 c.v.	XS 2 $\bar{x}$	XS 2 c.v.	XS 3 $\bar{x}$	XS 3 c.v.	
4	24.26	1.828	27.00	0.000	23.74	4.375	over-age/
6	31.61	21.167	34.58	20.756	27.03	5.098	mature
8	26.23	6.583	28.39	7.315	27.26	9.888	heather
35	25.32	7.35	27.30	9.100	23.87	9.281	
43	25.10	3.199	27.20	4.027	24.87	2.041	
69	23.24	2.570	24.00	0.000	24.20	3.156	
79	23.60	3.122	24.40	4.333	25.13	3.941	
85	24.57	7.742	25.57	8.096	22.71	3.328	
91	23.50	2.869	24.00	0.000	22.92	2.917	
2	24.68	3.647	26.88	4.721	23.20	8.798	mature/
19	25.03	5.251	26.90	5.994	23.83	4.100	building
22	24.68	3.647	26.88	4.721	23.20	8.798	heather
27	29.77	5.478	32.50	5.266	29.50	6.512	
39	24.90	5.503	26.60	5.660	23.50	3.009	
77	23.82	2.010	24.67	5.104	26.41	4.797	
87	28.00	5.144	30.14	6.105	27.79	10.656	
26	23.52	2.889	24.71	5.298	23.33	3.130	
1	34.50	4.912	37.98	4.480	27.40	6.770	young/
17	24.15	7.608	25.26	9.640	23.89	4.066	regenerating
18	34.00	3.589	37.96	4.278	26.65	6.946	heather
21	33.62	2.739	37.33	3.527	27.62	6.525	
28	29.21	9.490	31.95	10.716	27.34	7.347	
33	33.85	2.919	37.20	3.216	26.55	7.278	
38	28.93	2.128	31.14	1.716	19.21	3.640	
51	25.55	2.233	28.94	1.241	28.03	3.624	
73	30.67	3.499	33.25	5.608	24.83	10.134	
80	33.86	2.057	37.12	2.996	25.14	8.735	
83	26.92	6.690	28.60	7.757	26.00	6.093	
88	32.78	6.892	35.30	7.992	24.18	8.267	
74	35.29	3.153	39.14	2.731	25.00	2.309	
40	33.44	4.329	37.13	3.322	26.63	6.145	
34	27.60	3.791	29.80	3.373	18.05	5.230	
36	26.58	4.028	28.47	3.178	18.95	14.767	new burns
41	26.78	2.969	28.74	4.353	17.30	9.617	
42	26.87	2.766	29.13	1.773	18.00	2.100	

Appendix 2: Table 3. Summary statistics of response for heather canopies, airborne SPOT HRV data May 1984

Site	XS 1		XS 2		XS 3		
	$\bar{x}$	c.v.	$\bar{x}$	c.v.	$\bar{x}$	c.v.	
4	54.24	9.257	53.76	9.645	80.27	6.192	over-age/
6	54.71	1.913	54.00	2.171	87.41	4.185	mature
8	54.39	2.533	53.77	1.893	85.00	8.705	heather
35	57.93	3.815	56.69	3.825	79.61	5.611	
43	55.72	2.465	54.50	1.764	91.19	5.957	
69	50.04	1.776	49.72	1.791	85.24	6.446	
79	50.80	2.126	50.60	2.140	80.48	5.060	
85	52.83	3.032	52.50	2.333	76.00	4.633	
91	50.25	3.807	49.75	3.748	76.75	5.126	
2	54.26	5.578	53.58	4.797	81.44	15.656	mature/
19	54.75	4.498	53.92	4.652	81.38	5.279	building
22	55.32	6.009	54.61	6.540	79.68	10.570	heather
27	61.10	3.706	60.37	4.229	97.43	4.276	
39	53.33	2.228	52.56	2.186	84.83	8.406	
77	51.75	1.911	52.25	1.980	87.83	8.470	
87	53.29	2.289	52.21	2.013	80.96	3.612	
26	55.67	11.994	54.58	11.724	79.17	5.718	
1	61.03	13.24	60.85	14.240	82.31	16.481	young/
17	75.81	4.399	76.31	4.056	72.73	5.879	regenerating
18	73.40	4.501	75.14	5.272	73.70	11.557	heather
21	67.04	6.788	67.00	6.700	80.21	7.370	
33	74.00	1.328	73.93	1.174	69.53	6.517	
38	67.61	2.699	68.56	2.272	64.72	5.693	
51	69.25	2.864	69.00	2.480	59.19	9.258	
73	69.75	4.015	69.75	4.285	63.17	17.194	
80	73.05	2.302	73.67	2.709	59.29	4.035	
83	61.53	4.913	61.00	4.744	89.47	9.935	
88	71.50	2.617	71.79	2.742	65.93	11.994	
74	74.32	2.539	74.84	2.517	66.11	7.971	
40	71.12	5.297	71.40	5.722	82.22	13.165	
24	68.03	5.998	69.80	5.313	67.90	20.287	new burns
34	65.70	7.220	67.25	7.917	63.25	11.618	
36	63.85	3.494	65.85	3.825	56.45	5.986	
42	63.00	1.697	65.00	2.397	53.87	2.613	

Appendix 2: Table 4. Summary statistics of response for heather canopies, airborne SPOT HRV data, July 1984

	over-age/ mature	building/ young	young/ regenerating	new burns
4	x			
8	x			
17			x	
19		x		
21			x	
26		x		
36				x
39		x		
40			x	
42				x
43	x			
74			x	
85	x			
87		x		
88			x	
91	x			

Appendix 2 : Table 5 Representative test sites selected from airborne SPOT HRV data for further analysis. The test sites were numbered sequentially from 1 to 90 in the field, summary statistics for the full data set, i.e. sites which could be located in the central strip of the imagery at both dates, are given on the preceding pages.